Long-term weed dynamics and crop yields under organic and conventional cropping systems in the Canadian prairies

By

Dilshan Benaragama

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Canada

OR

Dean
College of Graduate Studies and Research
University of Saskatchewan
107 Administration Place
Saskatoon, Saskatchewan S7N 5A2
Canada

ABSTRACT

Differences in cropping practices, including tillage, inputs and crop rotations are the driving factors affecting weed dynamics (weed abundance, composition and crop-weed competition), which can ultimately affect crop yields. Several experiments were carried out to assess the impact of long-term organic and conventional cropping systems on weed abundance, weed community composition, crop yield and yield loss using a long-term (18 year) alternative cropping systems study (ACS) at Scott, Saskatchewan, Canada. The ACS study consisted of three input systems, namely high (conventional tillage), reduced (no-till conventional) and organic input systems and three crop rotation diversities (low diversity, diversified annual grains and diversified annual-perennials).

A statistical analysis of the 18-year rotation revealed that the organic rotations have four and seven times higher weed density and 32% and 35% lower crop yields than the reduced and the high input systems respectively. Weed community composition was consistently different in organic rotations compared to the two conventional rotations throughout the years, but year to year random variations were more profound. All cropping systems showed an increase in weed density, weed biomass and crop yields over time, probably due to an increase in rainfall over time. Increasing the crop rotation diversity with annual and perennial crops did not reduce weeds, but decreased crop yields in all systems. A two-year micro-plot experiment with four additional weed competition treatments on the ACS study revealed that the wheat yields were lower in the organic rotations even in the absence of weeds, implying that lower crop yields were due to soil fertility related factors. A greenhouse pot experiment from soils obtained from both organic and reduced rotations revealed that wheat yields were still lower in organic compared to the reduced input systems, even after excess mineral N and P were added. Furthermore, no differences in crop yield loss due to weed competition among cropping systems were identified. Overall, this study revealed that eliminating tillage and reducing inputs are possible without long-term changes in weed abundance, weed community composition or affecting crop yields. However, eliminating synthetic inputs as was done in the form of organic crop rotations resulted in increased weed abundance, changed community composition and decreased crop yields.

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DEDICATION

I would like to dedicate this thesis to my late mother Priyani De Silva and to my father Ranjith De Silva for their love, inspiration, and guidance. In addition, I like to dedicate this thesis to my wife Indika Benaragama and my daughter Thenuki Benaragama for the love and support.

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LIST OF ABBREVIATIONS

ACS	Alternative cropping systems
AIC	Akaikes information criteria
ANOVA	Analysis of variance
BM	Biomass
CCA	Canonical correspondence analysis
DAG	Diversified annual grain
DAP	Diversified annuals, perennials
EC	Emulsifiable concentrate
GM	Green manure
HIGH	High input
LOW	Low diversity
LSD	Least significant difference
ORG	Organic
MCPA	2, methyl, 4–chlorophenoxyacetic acid
PCA	Principal component analysis
PRC	Principal response curve
RDA	Redundancy analysis
SAS	Statistical analysis system
SOM	Soil organic matter

1.1 General introduction

Advancements in crop production technology have become necessary to feed the growing population ever since humans domesticated crops. At present, the challenge is enormous since the population is projected to increase to 9-10 billion by 2050 (Gerland et al. 2014). The Green Revolution, which began during the 1950's, prompted enormous changes in crop production to enhance the productivity of the agricultural lands to that from the pre-industrialized era by introducing high yielding varieties and synthetic inputs such as fertilizers, pesticides and herbicides. The green revolution transformed the cropping systems to rely on external inputs than ecological processes to manage soil fertility, crop pests and weeds (Gollin et al. 2005). Despite greater yields (Tilman 2001), there is a growing concern to move away from this high input conventional systems to low-input sustainable systems (Derpsch 1998; Zang et al. 2002) due to the negative impacts to the environment (Duesnbury et al. 2008; Guo et al. 2010) to agro-ecosystems (Bowman et al. 1999; Campbell et al. 2000; Janzen 2001), natural ecosystems (Carpenter et al. 1998; Tilman 2001) and to human health (Garry et al. 1996; Bouchard et al. 2010). Therefore, reducing tillage (Derpsch 1998; Zang et al. 2002) and organic farming systems (Rigby and Cáceres 2001; Willer et al. 2010) becoming more popular. Thus, the transition from input intensification to ecological intensification of crop production (Bommarco et al. 2012) is becoming the next paradigm shift in crop production.

Weeds compete with crop plants for limited resources and thereby can cause yield losses even up to 50% (Harker et al. 2001; Johnson et al. 2004; Oerke 2006). Weeds can be more difficult to manage under changing cropping practices as they are biological entities subjected to adaptation (Thompson 1999; Palumbi 2001; Neuhauser et al. 2003; Neve et al. 2009). Cropping systems are diverse with a wide range of disturbances, frequencies and timing in terms of tillage, fertilizer application, herbicide application, crop seeding and harvesting in which they act as diverse ecological filters to select particular species or community (Booth and Swanton 2002). The more diverse the cropping systems the more diverse the selection pressure, thereby it disrupts the favorable environmental conditions for a particular species.

Substantially lower crop yields (20-30%) in organic systems compared to conventional systems (Seufert et al. 2012; Poinsio et al. 2015) are one of the main reasons for the low adoption of organic crop production. Managing soil fertility and weeds are the most common crop production challenges for organic cropping systems due to inadequate alternatives for the external synthetic inputs. Managing weeds in conventional systems is also difficult due to rise in cost of herbicides, the negative impacts of herbicides and increasing resistance to herbicides (Heap 2015). Furthermore, in conventional systems, reducing tillage is known to be environmentally sustainable, but it can result in an increase weed abundance and cause changes in the weed community composition (Swanton et al. 1993; Derkson 2002; Sosnoskie et al. 2006). Therefore, there is a need to assess the impact of different cropping systems on weed abundance and community composition in order to devise better weed management strategies.

Cropping systems not only influence weed abundance and composition, but can influence the intensity of crop-weed competition, thereby causing differences in crop yield losses (Ryan et al. 2009; Smith et al. 2010). Therefore, there is a potential to enhance crop tolerance to weed competition by better cropping practices. According to Smith et al. (2010), increasing the diversity of soil resources can be a key component of increasing crop tolerance to weed competition. Still, the impact of cropping systems on overall weed dynamics (weed abundance, weed composition and yield loss due to weed competition) is less studied under diverse cropping systems in a given region. Also, the impact of cropping systems on weed dynamics widely varies depending on the farming conditions and need to be assessed locally. Therefore, understanding the agro-ecosystem processes and their functions on weed dynamics is the key to constructing sustainable crop production systems.

Cropping systems in the Canadian prairies have evolved from tillage-based, low-diversity rotations to no-till systems with more diverse crop rotations (Lafond et al. 1992; Dhuyvetter et al. 1996; Zentner 2002). Furthermore, organic systems have gained popularity in the prairies (Statistics Canada 2011). Even though we have a general understanding of the effect of crop management practices on weed abundance and weed composition, these dynamics can differ based on the overall cropping systems practiced in a region. Furthermore, the sustainability of these cropping systems in terms of weed management and crop yields is not well known. Due to the diverse environmental and geographic conditions among farms, cropping systems impact on weed dynamics and crop yields can vary. Therefore, comparing these diverse cropping systems in a single cropping systems experiment can aid in understanding the cropping system’s effect on weed dynamics and crop yields. Furthermore, due to the continuous presence of weeds in organic systems, impacts of soil fertility on crop yields may often be confounded in these systems.

Therefore, the relative influence of soil fertility and weed competition on crop yields in organic systems is not known. Hence, there is a need to understand the impact of weeds and soil fertility on crop yields in organic systems.

The long-term alternative cropping systems (ACS) trial at Scott, Saskatchewan, Canada maintained by Agriculture Agri-Food Canada is a unique experiment as it is the only long-term (18 year) study that compares organic, reduced input (no-till) and high input (conventional tillage) systems under three crop rotation diversities (low diversity, diversified annual grains, diversified annual and perennials) in the Canadian prairies. Therefore, the overall objective of this PhD thesis is to utilize this long-term cropping systems study in order to understand long-term weed dynamics and crop yields under diverse cropping systems in the prairies. The overall hypothesis of this PhD project is that the long-term practice of diverse cropping systems in the Canadian prairies differentially affects weed abundance, weed community composition and crop-weed competition; thereby, causes differences in crop yields. Accordingly, the following research objectives will be achieved. 1. The effect of eliminating tillage and reducing synthetic inputs in conventional cropping systems on weed abundance and composition. 2. The impact of eliminating synthetic inputs in the form of organic farming on weed dynamics and crop yields, 3. The effect of increasing the crop rotation diversity on weed abundance, composition and crop yields, 4. The effect of diverse cropping systems on crop-weed competition and 5. The main yield limiting factors in organic compared to conventional cropping systems. Overall, this thesis will provide a comprehensive understanding of the long-term weed dynamics under diverse cropping systems in the prairies.

1.2 Organization of the thesis

The research results presented in this thesis follow a manuscript format. The four experimental studies are contained in chapter’s three to six. Out of the four research chapters the first two chapters (chapter three and chapter four) include a historical data analysis of weed and yield data collected from the ACS trial for 18 years. These two chapters will describe the long-term impact of diverse cropping systems on weed density, weed biomass and weed community composition and crop yields in the ACS study. Chapter five describes crop-weed competition between organic and conventional no-till (reduced input) systems in a wheat phase in the last two years (2011 and 2012) of the ACS study. Chapter six of this thesis presents the results from a greenhouse study where crop-weed competition was assessed between organic and conventional systems under non-limiting soil N and P conditions. Chapter seven contains the general discussion, overall conclusions and future directions.

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2.0 LITERATURE REVIEW

2.1. Introduction to weeds

"Weeds have been a constant and intimate companion of man throughout his history and could tell us a lot more about man, where he has been and what he has done, if only we knew more about them." Harlan (1982).

Weeds are plants exist in disturbed habitats such as crop fields, pastures, plantation forests, rangelands and aquatic habitats. Agricultural weeds are the plants that have interfered with human activities ever since the time humans started cultivating crops by disturbing natural ecosystems (Snir et al. 2015). Weeds interfere with crop production and most of the time negatively impact the yield and quality of the crop resulting in substantial economic losses. Therefore, weeds in general are defined as plants objectionable and unwanted that interfere with human activities. However, weeds have been defined in numerous ways, depicting their characteristics and their impacts. Therefore, weeds are also synonymously termed colonizers and invaders depending on the perspective of the definition (Rejmanek 1995). Accordingly, based on biogeographical, ecological and anthropogenic viewpoints, weeds are plants that are native or introduced species (alien) that colonize disturbed habitats and interfere with human objectives causing negative ecological or economic impacts on agricultural or natural ecosystems.

In terms of global crop losses to pests, weeds are ranked number one compared to other pests in agriculture incurring yield losses up to 34% (Oerke 2006). In a survey in Canada of 58 crop commodities, it was identified that annual losses to weeds are worth of $984 million with the majority ($612 million) from western Canada (Swanton et al. 1993). Weeds not only reduce crop yields, but also affect the aesthetic value of the ecosystems and can harm human health (Bridges 1994). Hence, controlling weeds has been given priority in crop production.

2.2 Ecology and evolution of weeds

From an ecological perspective, agricultural weeds are plants that successfully colonize disturbed but potentially productive sites and are able to persist under continuous disturbances

(Mohler 2001a). There are two perspectives of weed evolution that can be identified. According to Baker (1974), weeds are believed to be a specific set of plant species that are pre-adapted with a specific set of traits or a general purpose genotype ideal for proliferation and adaptation under agricultural ecosystems. High fecundity, rapid growth rate from vegetative to reproductive phase, phenotypic plasticity, and high tolerance to environmental heterogeneity are thought to be some of the common most important traits in weeds. However, others suggest that adaptive evolution takes place in weeds where rapid evolution take place in weeds due to prevailing environmental changes and due to management factors which assists in their survival under changing environmental conditions (Thompson 1999; Palumbi 2001; Neuhauser et al. 2003; Neve et al. 2009). Since both perspectives of weed evolution are important, most problematic weeds may be considered to have some weedy characteristics, which are then subjected to rapid and localized adaptive evolution over time under changing environmental conditions.

2.3 Agro-ecosystems and weed evolution

Plants that were pre-adapted to natural disturbances were the first type of plants selected for domestication by humans. Wild colonizing plants are believed to have existed even before agriculture began and were opportunistic in terms of fluctuations in environmental conditions to colonize (Snir et al. 2015). These wild colonizing species are believed to be the plants that were domesticated by humans (De Wet 1966). During the domestication process, wild plants were gradually adapted by humans to the changing environments in agro-ecosystems. The domestication of wild plants to crops was a continuous process. During the crop domestication process, simultaneous, unintentional parallel adaptive trait selection process (co-evolution) occurred in other species co-existing with the crops. These plants eventually evolved into agricultural weeds (Harlan and De Wet 1965). Co-evolution involves reciprocal natural selection between two or more groups of organisms with a close relationship without any genetic exchange (Guglielmini et al. 2007). This co-evolution is evident from the fact that over 40 percent of the world's worst weeds belongs to Asteraceae and Poaceae families which also produce most of the world's food. Colonization of agriculture fields by wild plants is more common. Wild plants that become weeds are believed to be generalists that can survive under a wide range of environmental conditions and then gain specific weedy traits with co-evolution.

Barnyard grass (*Echinochloa crusgalli* L.) is the most classic example for such weeds that mimic the phenology of the cultivated rice to survive in the agro-ecosystem.

New weed species can develop from hybridization between crops and their wild relatives (Harlan 1982; Ghersa et al. 1994). Hybridization of crops with wild relatives can result in crops obtaining weedy traits from wild, and weeds obtaining traits adapted to agriculture ecosystem from the crop. Weedy sunflowers (*Helianthuis annuus* L.), weedy beets (*Beta vulgaris* L.) are such instances of hybridization with the crop. Weeds also can originate from cultivated species that are abandoned or escaped from domestication (feral crops). Weedy rye (*Secale cereal* L.) and weedy rice (*Oryza sativa* L.) are the most common such weeds. In spite of the mechanisms a plant became weedy, adaptive evolution can take place in all weeds allowing them to persist under diverse environmental conditions. Genetic variation and selection pressure are the two prerequisites for plant evolution. In agro-ecosystems, the selection pressure is imposed by local environmental conditions as well as the crop and weed management practices.

2.4 Weed communities

2.4.1 Weed community assembly

A community is a collection of species that occur in the same space in a given time (Begon et al. 1999). According to the community assembly theory, biological communities are assembled and they follow trajectories (community states) through time governed by both biotic and abiotic factors (Diamond 1975). Membership in the community is bounded by environmental filters or ecological constraints acting on the species pools. Therefore, plant populations exist as components of a plant community determined by the assemblage of species that occur in the same space and time (Begon et al. 1999). The species pool is a collection of all species that can colonize a given focal site (Srivastava 1999). This community assembly hypothesis is in contrast to the hypothesis that species occur in a given environment is a random subset of the species pool (McArthur and Wilson 1967; Weiher and Keddy 1999). According to the assembly theory, occurrence of species in a habitat is not random, but determined by the rules that set how niche space could be divided for co-existence among species (White and Jentsch 2004). As all biological communities, weed communities also believed to be assembled (Booth and Swanton 2002).

Even though plant communities are believed to be assembled they are not static and may not always be in equilibrium, but they insistently change in response to the internal and external cues (Booth and Swanton 2002). Plant communities differ in their responses to disturbances as plant species are unique in their regeneration requirements (Grubb 1977). Agricultural weed communities can be highly dynamic as their environment vary over time either due to anthropogenic or natural phenomenon. The main determinants of the community assembly are dispersal constraints, environmental constraints and internal dynamics (Keddy 1992, Belyea and Lancaster 1999). In agricultural ecosystems, weed community assembly is also determined by crop management practices. Human intervention in agriculture systems is the main difference between plant communities of natural ecosystems and in agro-ecosystems, therefore, more focus is needed to understand crop management induced weed community dynamics in agro-ecosystems.

2.4.2 Species pools

Species pool is a collection of all species that can colonize a given focal site (Srivastava 1999). Community assembly could be better understood by identifying the different species pools in an ecosystem since assembly rules act upon these various species pools to determine the community. Belyea and Lancaster (1999) illustrated that there are many types of species pools which superimpose to determine a particular type of community (Figure 2.1). Dispersal constraints limit the species pool to a particular geographic region (geographic species pool), abiotic factors limit the species pool to a particular habitat (habitat species pool) and the ecological species pool is the overlapping component of the above two species pools. Finally, the internal dynamics (competition, predation) within the ecological species pool determine the assembly of the plant community (Figure 2.1).

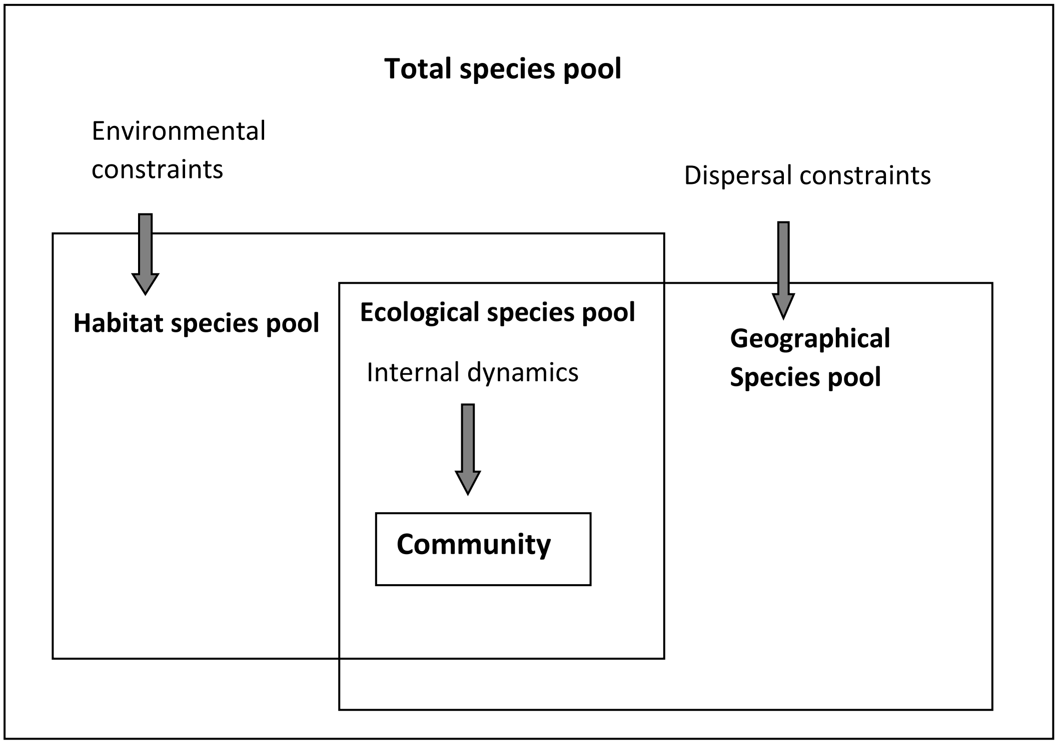

Figure 2.1. The relationship among four types of species pools and the processes that determine the membership within each species pools. Adapted from Belyea and Lancaster (1999).

2.4.3 Assembly rules

2.4.3.1 Dispersal limitation

Most agrestral weeds have relatively poor adaptations to disperse, thus require human intervention to spread locally and in a wide geographical range. Weed seeds can disperse by contamination with crop, soil, carried by livestock externally or internally and transported by machinery or irrigation water (Holzner and Numata 1982). Dispersal limitations determine the number of species and their amount of propagules arrive on to a particular site. Even if the species arriving at a site are kept constant, different communities can result due to the sequence of their arrival, frequency and the rate of species introduction (Booth and Swanton 2002). The species order of arrival can determine the ultimate community composition (Abrams 1985;

McCune and Allen 1985). Once arrived, weeds (geographic species pool) undergo different ecological and physiological processes that determine their establishment, growth and reproduction. Weed seeds usually have dormancy mechanisms that allow them to survive harsh environmental conditions and germinate when favourable conditions prevail. Seed dormancy is an important trait in weeds for long-term persistence in disturbed habitats (Guglielmini et al. 2007). Under most circumstances, most weed seeds persist in the soil seed bank and act as the main seed source of the new generation.

2.4.3.2 Environmental constraints

From the total species pool, the plant species that pass through the environmental filters (constraints) are more likely to compose the habitat species pool. The abiotic environment is highly dynamic, creating challenges and opportunities for individuals to establish. In agro-ecosystems, the environmental variations can be either less stressful where most species can survive or can be extreme that can determine the species composition depending on the type of species that can withstand these extreme conditions (Booth and Swanton 2002). However, plant communities will not always respond to the environmental perturbations (Weiher and Keddy 1999) since these environmental filters may not be always strong or species can escape these filters due to their genotypic diversity and phenotypic plasticity. Weeds are thought to be more plastic than non-weedy plants; hence, could be able to pass through most of the environmental filters. Furthermore, weeds with persistent seed bank could be the ideal escape mechanism for environmental constraints. However, besides normal environmental regulations of community pattern, drastic seasonal shifts in climate can be more important components of assembly rule processes (Drake 1990).

2.4.3.3 Internal dynamics

Even when plant propagules arrive and successfully establish within a habitat, not all species will eventually constitute a particular plant community. Once emerged, plants always interact with the surrounding biotic environment (internal dynamics) in order to obtain growth resources such as nutrients, light, and moisture. Furthermore, the internal dynamics such as competition, herbivory act on the ecological species pool to determine the community structure and composition. Competitive interactions among plant communities are considered to be ecologically significant because of their great potential for shaping patterns of distribution, abundance and the traits of competing species (Gause 1934). Even though competition does exist in plant communities (Grace and Tilman 1990) the exact mechanism of competition as an ecological filter is poorly understood. However, competition for resources can be considered as a filter in community assembly as it can cause even speciation (Aldrich and Kremer 1997). Even though internal dynamics and environmental constraints are considered as separate filters for community assembly, these two factors interactively determine a community. The competitive mechanisms, the intensity and their direction can be varied depending on the underlying environmental conditions or disturbance regimes (Belyea and Lancaster 1999). Thus, under different environmental conditions species with differential traits will have differential advantages. For instance, competition for moisture will be trivial after rainfall and subsequently light will be the limiting resource. Therefore, tall species will benefit than species with deep root systems. The random fluctuations in the environment may weaken or interrupt internal dynamics but may not preclude the importance of the process in structuring the community (Chesson and Huntly 1988, 1997). Furthermore, it can be a two way process whereby plants and the environment in which it exist affect each other (Vandermeer 1989; Guglielmini et al. 2007).

2.5 Crop-weed competition

Competition within crop-weed communities often determines the productivity of agricultural systems. In agro-ecosystems, crops and weeds compete with each other for resources. These interactions are believed to have influence on the shape, morphology and life history of individual plant of the weed community (Radosevich et al. 1997). The crop-weed community is determined by the growth limiting factors (quantity and variability of resources which is minimum required) and the tolerance levels of species (Odum 1971). A crop either can suppress weeds by pre-empting growth resources or can tolerate weed competition reducing the yield loss. The crop's ability to suppress weeds is mainly determined by genetically controlled characteristics such as plant height, relative growth rate, leaf area index (Huel and Hucl 1996; Lemerle et al. 2001) and therefore we can observe differences in competitive ability among crops (O'Donovan et al. 1985; Lemerle et al. 1995; Fischer et al. 2001) as well as among crop cultivars (Zhao et al. 2006; Benaragama et al. 2014). Importantly, cultural practices such as higher seeding rates (Benaragama and Shirtliffe 2013) and narrow row spacing (Koscelny et al. 1990; Fanadzo et al. 2007) also can contribute to increased crop competitive ability (O'Donovan et al. 1999; Olsen et al. 2004). In contrast, crop tolerance to weed competition has been found to be less controlled by genetic mechanisms and more often by environmental factors (Cousens and Mokhtari 1998; Ruiz et al. 2008; Benaragama et al. 2014). However, the factors governing crop tolerance to weed competition are not well understood.

Crop yield loss due to weed competition is well known to increase with an increase in weed density (Cousens 1985). Yet, other biological and ecological factors of crop and weed could alter this basic relationship resulting in either an increase or decrease in yield loss making it complicated to predict yield loss solely due to weed abundance. Plant competition for resources can vary depending on the species traits (crop and weed) and the type and the timing of the availability of resources. Accordingly, the diversity in species (both crop and weeds) and the diversity in resources could alter crop-weed competition. Understanding crop-weed competition in relation to all the above factors may result in reduced yield loss as well as an influential factor regulating weed population and community dynamics in agro-ecosystems. Climate, soil, biological factors and crop management practices can influence the balance in either favour of the crop or the weed. When the weed is favoured not only the abundance and distribution of weed could be high, but crop yield loss due to weed competition could increase. Furthermore, the understandings on plant coexistence based on niche separation (Gause 1934; Silvertown 2004) provided further insights to understand crop-weed competition.

2.6 Weed diversity

Biological diversity can be identified at different levels such as genetic, somatic, spatial, and temporal, species and trophic (Dekker 1997). Plant species diversity in a community is an outcome of several factors such as plant genetic resources, abiotic and biotic environments and crop management practices (Almekinders et al. 1995). Intensification of crop production practices and the use of herbicides are known to have reduced weed species diversity in crop lands (Chancellor and Froud-Williams 1986; Johnson and Coble 1986; Bischoff and Mahn 2000). The impact of the plant diversity on community and the ecological functions of an ecosystem is debatable as there are two theories. According to the species redundancy hypothesis, there is a minimum diversity required for the functioning of the ecosystems and beyond that species are redundant in their roles (Walker 1992). In contrast, the diversity-stability hypothesis asserts that diverse communities are more stable as they resist and recover from disturbances. This occurs because a greater diversity in species allows for differences in ecological functions (Kikkawa 1986). The idea of diversity leading to stability may not be applicable to all ecosystems (Goodman 1975; Walker 1989). In modern agriculture, since productivity is considered more important than stability or sustainability, the concept of diversity can be counterproductive (Hall and Clarke 1995; Brummer 1998).

Species diversity generally refers to the species number (richness) and their relative abundance (evenness) (Magurran 1988; Tonhasca 1993). Both of these aspects of diversity are important to understand diversity in a community since two communities with identical number of species (richness) can differ in terms of evenness. Therefore, composite diversity indices which incorporate both species richness and evenness are often used to describe species diversity (Tonhasca 1993; Clements et al. 1994). The most commonly used composite diversity indices include the Shannon-Weiner index (Shannon and Weiner 1949), Simpson's index (Simpson 1949) and alpha (a) of the log series index (Fisher et al. 1943). Each index has its own advantages and disadvantages and the choice depends on the data set utilized (Magurran 1988; Clements et al. 1994). These diversity indices can be utilized to capture some of the effects of cropping systems on weed communities, but not the total dynamics of communities. Changes in community diversity due to agronomic practices are well known, particularly the effect of herbicides, tillage (Odum et al. 1994) and crop rotation (Stevenson et al. 1997). Importantly, less is known about the overall impact of cropping systems on weed community diversity. From a weed management perspective, the dominance of few weed species can cause complications in long-term weed management. Weed communities with dominant species have a better chance for adaptations to weed management practices through novel genetic variation by increased mutations and recombination potentially making them rather difficult to control over time (Nerve et al. 2009). Hence, maintaining a more even species community is usually considered a better option.

2.7 Agroecosystems and weed dynamics

2.7.1 Weed population dynamics

Weed population dynamics (birth and death) are mainly internally controlled due to intraspecific interference. Furthermore, the external factors (environment) vary between generations and within a generation, thereby can affect the species population growth rate and its potential equilibrium population density (Cousens and Mortimer 1995). In agro-ecosystems, the external factors could be further understood in relation to environmental factors, crop management practices and interactions between other organisms (weeds, pests and pathogens) (Cousens and Mortimer 1995). Therefore, weed floristic composition and species adaptation are assumed to follow the temporal pattern of environment change resulting from interaction between climate variables and agronomic variables related to a particular farming system (Ghersa et al. 1994). The environmental factors also known as stochastic processes influence the population dynamics due to the random variations in birth and death rates caused by weather or any form of abrupt disturbances in the environment. The deterministic process which are more consistent occur due to the interactions between biotic components in a community and other predictable ecological processes (Freckleton and Watkinson 2002). The random fluctuations in weed abundance impose great difficulties in predicting weed abundance and planning weed control strategies accordingly. However, changes that occur due to deterministic factors are more predictable and can be manipulated in favour of the crop than the weeds. In agro-ecosystems, there can be diverse deterministic factors acting upon weeds that influence both population and community dynamics. Therefore, it is unlikely that a single factor will determine the attributes of a weed community, but the relative importance of different factors could highly vary (Légere and Samson 1999). Since both these extrinsic and intrinsic factors shape up the weed community, it is vital to understand all these factors to understand weed dynamics in an agro-ecosystem.

2.7.2 Crop management and weed dynamics

The weed community in a crop field can be a reflection of the prevailing environmental conditions (stochastic events), as well as agronomic practices applied (deterministic processes) in the field (Lososová et al. 2004; Fried et al. 2008). Agricultural lands are frequently disturbed either due to herbicides, grazing, burning or tillage. After crop has emerge there is a high demand for nutrients and then crop develops a canopy which covers up the soil suppressing weeds that might emerge later. Therefore, crop land undergoes different disturbances with periods of live plant cover is very high and the soil resources are low, followed by no plant cover but high soil resources (Gugliemini et al. 2007). These forms of frequent and consistently disturbed habitats are the key features in agro-ecosystems. Such continuous, predictable, cyclic pattern of disturbances can provide assembly conditions for naturally occurring weed communities (Ghersa 1994). Weed communities undergo strong selective forces imposed by human that determines the species survival, evolutionary pattern and succession (Harlan 1982).

Therefore, in agro-ecosystems weed community dynamics (abundance, composition and fecundity) are highly governed by crop production practices. Crop type (Smith et al. 2006; Fried et al. 2009), crop sequence (Bohan et al. 2011), sowing date (Gunton et al. 2011), tillage systems (Cardina et al. 2002; Sans et al. 2011) and herbicide application regime (Dieleman et al. 1999) have all been found to explain a large part of the variation in weed communities among fields.

Disturbances in agro-ecosystems can cause weed community changes in relative abundance or species composition. Disturbances causes selection pressure, which eliminates susceptible species from the existing community and allows surviving species or biotypes to increase in abundance (Derkson 2002; Manley 2002). The occurrence of regular disturbances in agro-ecosystems disrupts the natural succession of weed communities. Therefore, despite the natural environmental variations, human intervention in agricultural systems is an important determinant of weed abundance, distribution, composition and competitive ability. Differences in weedy species in seed dormancy mechanisms, emergence patterns, growth plasticity, life cycle and overall life duration, shade tolerance, competitive ability, seed dispersal mechanisms, as well as the morphological and physiological variation can contribute to a community response to management practices.

Compared to natural ecosystems, arable lands are characterized by regular, recurring and highly predictable disturbances (Froud-Williams 1988). Weeds thrive in agro-ecosystems compared to wild species which are more adapted to unpredictable disturbances (De Wet and Harlan 1975). Crop management practices are important drivers of weed community dynamics (Dale et al. 1992, Derksen et al. 1993; Menalled et al. 2001). Some species react positively by increasing their abundance and distribution while others fail to survive (Radosevich et al. 1997). Human intervened disturbances occur in agriculture land due to intense management of crop via tillage, fertilizer application, herbicide application and harvesting operations. Therefore, the spatial distribution and abundance of weeds are highly determined by a wide range of cultural practices in cropping systems. In a broad sense, crop production practices can be categorized as tillage, crop rotation and weed control practices (Aldrich and Kremer 1997). These management practices can exert selection pressures (filters) at different life stages i.e., seed, seedling, and reproductive. Furthermore, timelines of different crop management practices have various impacts on weeds at different growth stages. Cropping practices also cause evolutionary changes in weed traits related to seed germination, leaf shape, flowering pattern, seed shattering, seed size and shape and herbicide resistance (Radosevich et al. 1997). Realizing that cropping practices can act as ecological filters which create assembly conditions can provide the framework to determine and predict weed community dynamics.

2.7.4 Impact of tillage on weed dynamics

Tillage is the most important crop management practice that changes the soil conditions (physical, chemical, and biological processes) in arable land; thus, it can be considered as a primary environmental filter for the above and below-ground weed community. Tillage creates different micro-environments for weed seeds due to the differences in porosity, bulk density and soil surface conditions at the time of planting (Lal et al. 1994). Plants differ in their abundance and distribution mainly due to differences in the availability of micro-sites for germination (Grubb 1977) and their germination niches. The availability of micro-sites depends on the soil physical, chemical and biological properties which can be altered by different tillage practices used in crop production. Alterations in soil conditions can lead into differences in species abundance that ultimately shape the community (Harper 1977). Recently tilled soils tend to be warmer, have higher diurnal temperature fluctuations, higher nitrate concentration and better aeration relative to undisturbed soils (Gebhardt et al. 1985; Cox et al. 1990). Weed seeds require adequate moisture, aeration and temperature for the germination. These conditions are more favourable for germination in the upper soil layer. Tillage intensity affects weed emergence, seed production, vertical distribution and density of weed seed banks in arable lands (Buhler 1995). Vertical distribution of seeds in the seed bank is a critical factor determining seed survival, germination and emergence (Mohler 1993). A review of studies by Mohler (2001a) concludes that after a single moldboard plowing, vertical seed distribution follows a skewed normal distribution of density with increasing depth. However, with other implements a monotonic decline in weed density was observed. Yet, with multiple operations with either implement, seed distribution became more uniform with depth. Tillage not only inverts soil, but also enhances the decomposition of organic matter; thereby, increase nitrate levels in the soil. Enhanced nitrate levels in the soil can increase germination of weed seeds (Pons 1989).

Disturbance caused by tillage re-initiates ecological succession, which results in the weed community being dominated by annual species instead of perennials (Mohler 2001b).

Conventional tillage is usually accomplished by moldboard plow and subsequent secondary tillage is practiced with a disk plow. Moldboard plowing inverts the soil and consequently bury growing weeds. Tillage is an effective weed control method especially good at controlling perennial weeds regenerated from underground vegetative organs (Conn 1987). Despites its weed control benefits, moldboard plowing has been replaced with conservation tillage due to environmental concerns, specifically the high rate of soil erosion associated with plowing (Larney et al. 1994). Conservation tillage is the reduction in tillage while maintaining a crop residue cover of at least 30% on the soil surface (Swanton et al. 1993). Conservation tillage either can be reduced tillage practiced with chisel plow or zero till (no-till). The differences in soil disturbance levels influence the soil seed bank composition.

A persistent soil seed bank can be the result of conventional tillage since most seeds being buried in deeper soil layers. These buried seeds may germinate when returned to the surface by subsequent tillage operations. In contrast, seeds in a conservation tillage systems are mainly distributed on the top layer of the soil (Cardina et al. 1991; Ball 1992; du Croix Sissons et al. 2000), and these seeds are more vulnerable to losses due to weed management practices, exposure to harsh environmental conditions and seed predation. Therefore, the impact of tillage on subsequent weed populations depends on the long-term history of tillage practices and the distribution of seeds in the soil profile. Hence, generalizing the short-term impacts of tillage or no-till on weed dynamics is difficult.

Reduced mechanical disturbances can trigger a systematic replacement of species causing a different weed community. The germinable weed seed community composition in no-tillage differed from those in conventional and minimum tillage (Sosnoskie et al. 2006). Cardina et al. (1991) identified that no-till systems have reduced weed seedbank populations compared to moldboard plowed systems. Accordingly, many studies (Froud-Williams 1983; Froud-Willlliams 1988) reveal weed community shifts under conservation tillage practices. Perennial weed species have been found progressively favored over annuals (Cardina et al. 1991; Swanton et al. 1993; Moyer et al. 1994; Zanin et al. 1997) and annual dicot species favoured under conventional tillage (Froud-Williams et al. 1981; Derksen 1993). Furthermore, reduced tillage is generally believed to be associated with weed communities dominated by annual and perennial grass species as well as wind-disseminated crops and volunteer crops (Froud-Williams 1988; Légère and Samson 1999). Most often, the effects of agronomic practices on weed community dynamics are confounded by the other crop management practices associated with cropping systems. Thus, changes in weed communities predicted with cropping systems have ignored the confounding effect of several other weed management practices (Buhler 1995; Derksen 1996). For instance, the dominance of grasses over broadleaf weeds may be a result of greater herbicide efficacy on broadleaves than tillage effect (Froud-Williams 1988). In general weed species dominance is due to interactions between weed management, crop rotation and tillage (Légère and Samson 1999).

2.7.5 The effects of crop rotation on above and below-ground weed dynamics

Crop rotation is the practice of growing different crops on the same land from year to year, and provides temporal diversification in the crops. Crop rotation and tillage were the main weed control tactics used until the recent past before the development of herbicides (Froud-Williams 1988). Crop rotation is an age old practice used to fulfill many objectives such as to improve nutrient status, soil structure, soil conservation and suppression of plant diseases (Smith et al. 1987; Karlen et al. 1994). Improved weed control associated with crop rotation can be one of the main reasons other than improved soil fertility for the gaining popularity of crop rotations in present cropping systems, particularly in low-input and organic cropping systems (Liebman et al. 2004). Crop rotation mainly helps to manage weeds due to the differences in production practices associated such as time of seeding, harvesting and herbicide rotations (Johnson and Coble 1986; Weston 1996). The differences in these attributes among different crop species in the rotation impose unfavorable conditions for weeds to germinate, grow and produce seeds. Rotating crops with functionally different species (annual vs. perennial, monocot vs. dicot) can eliminate one or more closely adapted weeds compared to the monoculture practice (Liebman et al. 1996). Thus designing effective crop rotations are the most fundamental approach in ecological weed management. According to Mohler and Staver (2001), crop diversity in agro-ecosystems should be developed to challenge weeds with a broad range of stresses and mortality factors by using crop sequences containing dissimilar species and management factors to pre-empt growth resources such as light, water and nutrients used by the weeds.

Different crop species, planting dates, management practices and competitive characteristics of the crops in the rotations disrupt the regeneration niche (Liebman 2004). Regeneration niche is the species-specific set of environmental conditions required to replace one generation from another of the same species (Grubb 1977). Continuous monoculture favours crop-weed associations due to similar regeneration niches. Therefore, a crop rotation should consist of varying patterns of resource competition, allelopathic interferences, soil disturbances, timings and the degree of mechanical damage to provide unstable and inhospitable environment for weeds to survive, grow and proliferate (Liebman and Dyck 1993). Furthermore, the overall differences in the type and timing of soil, crop and weed management practices are believed to cause more mortality in weeds in the rotation than in monoculture (Martin and Felton 1993; Liebman and Staver 2001).

Crop rotations have been found to influence weed seed density and composition both in the seedbank (Buhler 1999; Buhler et al. 2001; Cardina et al. 2002) and above ground (Blackshaw et al. 2001; Manley et al. 2002). Liebman and Dyck (1993) reviewed 29 crop rotation studies and identified that in the majority of studies, both above ground and below ground weed density was markedly lower in rotation compared to their particular monoculture. Hume et al. (1991) found that weed densities tended to be lower in wheat (*Triticum aestivum* L.)-fallow rotation than under continuous cropping within no-till and minimum tillage. However, there were some situations where crop rotation did not affect weeds indicating that all crop rotations may not work equally well to control weeds. Some weeds tend to associate with a particular crop since the same environmental conditions and cultural practices favor the crop also favours the weed (Radosevich et al. 1987). For instance, Teasdale et al. (2004) identified that in organic or low-input cropping systems, the inclusion of perennial forage or pasture crops in the rotation can reduce weed populations.

Crop rotations have also been identified to influence community structure (species diversity and richness) both above ground and below ground (Sosnowski et al. 2006). The size and composition of the germinable weed seedbank community is often associated with shifts in the aboveground weed community (Cardina and Sparrow 1996; Mulugeta and Stoltenberg 1997; Menalled et al. 2001). Widely variable environmental conditions due to crop rotations affect weeds and potentially favor evenness instead of dominance in weed communities (Légère and Samson 1999). Weed communities are more stable and diverse in cereal-forage rotations than cereal monoculture (Stevenson et al. 1997). Compared to monoculture, weed species diversity tends to increase in rotation (Stevenson et al. 1997). Marked periodicity in weed germination and periodicity in crop management practices (land preparation, seeding and herbicide application) interact to determine a specific weed community associated with particular crop rotation sequence (Leibman and Staver 2001). A 21-year crop rotation study under conventional tillage in Indian Head Saskatchewan identified that stinkweed (*Thlaspi arvense* L.) and common lambsquarters (*Chenopodium album* L.) were more abundant in wheat (*Triticum aestivum* L.) after fallow than they were on either two sequential wheat after fallow or on continuous wheat cropping. Green foxtail (*Setaria viridis* L.), thyme-leaved spurge (*Euphorbia serpyllifolia* Pers.), hairy vetch (*Vicia villosa* L.) and Canada thistle (*Cirsium arvense* L.) were the most abundant in continuous cropping (Hume 1982). Another long-term study in England conducted by Chancellor (1985) identified that spring germinated species such as *Aethusa cynapium* L. was most abundant in spring-sown crops (barley and potato), and fall-germinating weed *Poa annua* L. was most abundant in fall-sown crops (winter barley, wheat and oat).

2.7.6 Herbicides and weed dynamics

Herbicides are the predominant weed control tool used in conventional crop production systems. In general, herbicides tend to decrease the population of the susceptible species, even though it may not eradicate the species (Haas and Steibig 1982). With a reduction in susceptible species there can be a concurrent increase in species naturally tolerant to the herbicides applied (Chancellor 1979; Haas and Steibig 1982). Therefore, there can be a compositional change in weed communities due to long-term application of herbicides. Herbicides can have a large effect on the weed species composition by favoring species or biotypes that tolerate or avoid herbicides (Hume 1988). These species take advantage of the niches made available by the reduction or elimination of susceptible populations. Mahn (1984) found that persistent triazine herbicides reduced weed diversity over a four-year period. Similarly, increases in non-susceptible species after the introduction of 2,4-D and triazine herbicides have been noted (Hay 1968; Haas and Steibig 1982). In contrast, Derksen et al. (1995) found that the use of non-residual post-emergence herbicides did not affect the weed species diversity. In a 35-year study of the continued application of 2, 4-D, Hume (1987) found that species were not eliminated but community structure and species abundance changed. The use of herbicide resistant crops has been able to control problematic weed species due to more intense use of herbicides. However, these systems are vulnerable to new problematic weeds. For instance, a shift in the weed community has been observed in glyphosate resistant soybean and cotton cropping systems in the US (Culpepper 2006).

2.8 Sustainable agriculture

The word sustainability is descended from the Latin word "sustinere" which means to keep in existence or long-term support (Rigby and Cáceres 2001). Sustainability has emerged as an important aspect over the past few decades due to the depletion of natural resources with the growing world population. Since agriculture is the main anthropogenic activity that supplies food, fuel and fiber for humanity, achieving sustainability in agriculture is paramount. At present, the imprudent use of natural resources has caused an alarming threat to the stability of natural and agricultural ecosystems. Overuse of external inputs and the use of non-renewable energy sources in crop production is believed to interrupt the balance between human activities and ecosystem processes. In that context, achieving sustainable agriculture is gaining momentum throughout the world.

Due to the complicated processes in agriculture production practices and ecosystem processes, it is extremely difficult to determine which methods and systems are sustainable as they can vary both temporally and spatially (Rigby and Cáceres 2001). In general, reducing or prohibiting the use of external inputs, diversifying crops temporally and spatially and relying on natural ecosystem processes to supply nutrients and to control pest and disease are the key aspects of sustainable agriculture. In that perspective, low input agriculture (Edward 1987), biodynamic farming (Steiner 1924), organic farming (Scofield 1986) and permaculture (Mollison and Slay 1991) are several alternatives believed to be more sustainable compared to conventional high input agricultural systems. Among all, organic farming is considered to be the most consistent and the regulated approach to achieve sustainable agriculture. Nonetheless, some elements of sustainable cropping practices such as conservation tillage, integrated pest and disease management and integrated weed management have been already embraced by the conventional systems.

2.9 Cropping systems in the Canadian prairies

Around 85% of the crop production in Canada is carried out in the prairies. The Canadian prairie climate is continental with cold winters and short summers (Lafond et al. 2011). The majority of the grain based crop production is practiced in the prairies, which has a semi-arid to sub-humid climate. Four distinct soil regions can be identified in the prairies as Brown (Aridic Borols), Dark Brown (Typic Borols), Black (Udic Borolls) and Dark Gray (Udic Ustolls). Summer annual crops are grown mainly during the summer with seeding carried out in April-May and crop is harvested predominantly in August and September. Spring wheat was the main crop grown in the initial period of crop production in Canada as it was more adapted to the semi-arid climate and due to the high global demand (Strange 1954). During the 1980's, wheat continued as the dominant crop but approximately 30% of the land was uncropped and used summer fallow (tillage/chemical) for weed control and for moisture conservation (Statistics Canada 2006). Summer fallow involves leaving a land area uncropped for a growing season, thereby leaving the land with little plant cover for approximately 20 consecutive months. The practice of summer fallow has thought to begin in 1880's and by 1930 it was widely adapted (Carlyle 1997). Due to the limited moisture availability in the dry areas, particularly in the Brown and Dark Brown soil zones, summer fallowing was considered an essential practice. Wheat-fallow cropping system with extensive use of tillage for weed control was the standard crop production practice until 1980s. These systems produced greater yields and high economic return than continuous wheat (Zentner and Campbell 1988).

Frequent summer fallowing and extensive use of mechanical tillage for weed control was the key components for grain production in the Brown and Dark Brown soil zones in the prairies until recent (Zentner and Campbell 1988; Zentner et al. 1996). Crops sown on fallowed land were found to be more productive due to moisture conservation, nitrogen availability and better weed control. Frequent fallowing also reduced the risk of crop failure in unusually dry years, which was common in the Brown and Dark Brown soil zones. The advantage of nitrogen release in the fallow and greater ability to control weeds, particularly perennial weeds, made fallow common in many parts of the wet regions as well. However, the long-term practice of summer fallow threatened sustainability due to soil erosion, deterioration of soil organic matter content. Even though weed management was one of the main objectives of fallow, weeds still can be a problem in the succeeding crops after fallow (Hume 1982; Blackshaw et al. 1994). Furthermore, good crop rotations negate the need for a fallow phase for weed control (Walker and Buchanan 1982; Regnier and Janke 1990). Importantly, the lack of economic return during the fallow year made it less attractive as a management option. Other than these factors, improved seeding equipment, greater fertilizer and herbicide options have reduced the use of fallow systems in most regions (Lafond et al. 1990).

Due to the soil degradation and inefficient water use associated with summer fallow (Campbell and Zentner 1993; Biederbeck and Bouman 1994) adoption of conservation tillage became popular in the prairies and consequently enhanced the use of diverse cropping systems (Brandt and Zentner 1995). The adoption of conservation tillage in conventional agriculture has been found to reduce soil erosion, conserve soil moisture and increase soil organic matter (Lafond et al. 1992; Malhi et al. 2008). The discovery of efficient herbicides such 2-4 D and MCPA during the 1940s and 1950s and the synthetic fertilizers allowed for the adoption of continuous cropping. The potential to intensify crop production due to the popularity of synthetic fertilizers, diversification of crops with alternative cereals and oilseed crops and importantly the negative effects of fallowing thought to be the key factors that farmers tend to avoid in the prairies (Carlyle 1997).

The introduction of pulses and oil seed crops allowed the cropping systems to be more diverse and intensified in the prairies. Cultivation of broadleaved crops such as pulses and oil seeds was possible due to the practice of no-till since the moisture conservation was enhanced. Advancements in seeding technology and herbicide technologies are also believed to have accelerate the adoption of broadleaved crops in the prairies. Canola (*Brassica napus* L.), yellow mustard (*Sinapsis alba* L.) and flax (*Linum usitatissimum* L.) were the main oilseed crops adapted to cool climate in the Canadian prairies (Johnston et al. 2002; Gan et al. 2004). Due to the improvements in oil quality, canola became the most widely grown oilseed crop in Saskatchewan and in Canada (Johnston et al. 2002) and only second to wheat among all field crops grown (Statistics Canada 2011). Since canola has a deep tap root system, it can exploit water and nutrients from the deep soil profile (Johnston et al. 2002; Gan et al. 2009) allowing it to fit into crop rotations with wheat. Among pulse crops, field pea (*Pissum sativum* L.), lentil (*Lens culinaris* L.), chickpea (*Cicer arietinum* L.) faba bean (*Vicia faba* minor) and dry bean (*Phaseolus vulgaris* L.) are the most widely grown in western Canada. Field pea is the most seeded pulse crop in western Canada and Saskatchewan account for about 68% of all pulses grown (Statistics Canada 2011). Pulses are considered invaluable in crop rotations due to their nitrogen fixation ability with the association of soil microbes. Cereal crops grown following pulses in rotation have greater yields than cereals following cereals (Gan et al. 2003; Krupinsky et al. 2006; Bremer et al. 2011). Other than yield benefits, increased soil nutrient retention and cycling (Liebig et al. 2006; Gardner and Drinkwater 2009) decreased carbon footprint (Gan et al. 2011), reduced weed competition (Stevenson and van Kessel 1996; Cardina et al. 2002; Seymour et al. 2012) and reduced disease incidences (Krupinsky et al. 2002; Nayyar et al. 2009) are some of the other benefits of diversified cropping systems including pulses. Due to the heavy reliance on herbicides to control weeds in no-till cropping systems, the economic and environmental sustainability of these systems is challenged; hence, the long-term evaluation of these cropping systems in respect to yield, pest dynamics, soil health and economics are warranted. Furthermore, due the growing awareness of environmental impacts, rise of input costs, and price premiums, organic farming is a thriving industry in Canada. The prairie Provinces have the largest land area devoted to organic crop production in Canada accounting for 40% of cultivated organic land (Statistics Canada 2011).

2.10 Organic farming

Organic agriculture began in the early 20th century and is believed to be an outcome of the radical movement against fertilizers and pesticides in agriculture (Merrill 1983; Conford 2001). The first form of organic agriculture believed to descend from the ideas of Austrian spiritual philosopher Rudolph Steiner in the early 20th century who founded biodynamic farming (Steiner 1924). Practicing farming by perceiving and preserving nature was the core philosophy of organic farming. Later, Lady Eve Balfour and Sir Albert Howard initiated the awareness of organic farming by highlighting the importance of soil health and nutritional benefits of organically grown food (Howard 1947). The period between 1980 and 1990 thought to be the period of great revival in organic farming due to the increased attention on the environmental problems caused by modern agriculture (Kirchmann et al. 2008).

The International Federation of Organic Movements (IFOAM) defines organic agriculture as “a production system that sustains the health of soils, ecosystems and people”. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs (IFOAM 2006). Organic farming generally refers to crop production carried out without the use of synthetic agro-chemicals. Yet, it is more than merely substituting synthetic compounds with natural compounds (Anon 2002). Organic crop production relies upon ecological processes to manage pest, diseases and soil fertility. It should be self-sustaining and self-regulating entity through the use of low inputs and use of preventive ecological practices than using high external inputs (IFOAM 2006). Organic farming maintains its sustainability or self-sustaining ability by managing the unit as a closed system. It is considered an agro-ecosystem which means an ecosystem with crop production carried out with a strong interaction with biotic and abiotic components of the system (Swift and Anderson1993; Almekinders et al. 1995; Vandermeer 1995). The main challenge to any organic farmer is how to manage all these interactions at different levels to control pests, to manage soil fertility and to gain stable high yields with minimum resource use (Alteirie and Nicholls 1999). Farming systems are diverse around the world and organic and conventional systems are not defined by a set of particular practices; but they are an aggregate of a number of management practices determined by farmer choice depending on site-specific requirements; hence, making generalizations about cropping systems is quite difficult (Harrier and Watson 2003). Also in this perspective, farmer's knowledge and decision making play a vital role in the optimum design and the function of an organic farm.

2.10.1 Weed management in organic systems

Inadequate weed control is one of the most challenging constraints to achieving high crop yields in organic systems due the prohibition of herbicides. In conventional crop production, weed management is treated as an individual problem and solutions are usually prophylactic. In low-input and organic systems, a more ecological based holistic approach is needed with proper management of all the components of the agro-ecosystems (Liebman and Davis 2000). The main principle in holistic weed management is to use "many little hammers" which is to use cumulative and synergistic effects of diverse weed management strategies (Liebman and Gallandt 1997). The prime objectives of this holistic weed management are discouraging weed invasion, reducing weed population to tolerable levels, reducing the yield loss caused by weeds, and managing weeds composition to manageable levels (Liebman 2001; Harker et al. 2005). The integration of cultural, mechanical and biological weed control approaches can be used to achieve these objectives.

The first cultural approach in weed management in any cropping system is to establish a vigorous crop to pre-empt resources by occupying above ground and below ground space (Kolb and Gallandt 2012). Enhancing the crop competitive ability with competitive crops in the rotation is the most fundamental approach in cultural weed control. Crop competitive ability is the capacity of the crop to outcompete weeds for growth resources. Crop competitive ability can be determined by two mechanisms such as the ability of the crop to suppress weeds and the crop's ability to tolerate the weed effect on crop emergence, biomass and yield (Jordan 1993). Crop competitive ability can be enhanced by both genetic (Lemerle et al. 1995; Benaragama et al. 2014) and agronomic factors (Koscelny et al. 1990; Mohler 2001c; Benaragama and Shirtliffe 2013). Competitive crop cultivars (Lemerle et al. 1996; Paynter and Hills 2009; Benaragama et al. 2014), increasing crop seeding rate (Evans et al. 1991; Weiner et al. 2001; Olsen et al. 2004) and narrow row spacing (Murphy et al. 1996; Weiner et al. 2001) have been found to be successful in many instances in reducing weed density either in organic or in conventional systems.

In crop mechanical weeding is indispensable to control weeds in organic systems and it is the main direct weed control strategy practiced after the crop has emerged. Spring-tine harrowing is the most practiced mechanical weed control methods on organic farms (Rasmussen et al. 2004; Hansen et al. 2007). Harrowing uproots and buries weeds in the soil thus limiting their ability to regrow (Rasmussen 1991; Kirkland 1995). Harrowing at two to three leaf stage of the crop can reduce weed density by 50-80% (Velykis et al. 2009; Auskalnis and Auskalniene 2008; Benaragama and Shirtliffe 2013). The rotary hoe is not as widely used as spring-tine harrow but has a great potential. The main advantage of the rotary hoe over harrowing is that it can be used in cropping systems with high levels of crop residue (Shirtliffe and Johnson 2012). It can avoid crop damage and remove weeds between crop rows.

2.10.2 Soil fertility management in organic systems

Soil fertility in general terms is the ability of the soils to supply nutrients for plant growth. This narrow view of soil fertility is common in conventional agriculture where the prime objective is to supply essential nutrients. However, from an organic farming perspective, it is vital to understand soil fertility as an ecosystem process where there is an integration of soil biological, chemical and physical components (Watson 2002). Therefore, soil fertility refers to the interacting components of physical (water-holding capacity, structure, etc.), chemical (nutrient dynamics, pH), and biological (soil biota) properties of the soil. Well-managed organic matter, good soil structure, diverse soil biota and high nutrient and water holding capacity are the key components of a good organically managed soil (Koopmans and Bokhorst 2000). The key differences in terms of soil fertility among many cropping systems is driven by many factors such as the relative size of nutrients pools in the soil; the processes and the rates in which nutrients transform and transfer between these pools, the potential for losses of nutrients from the soil and other soil properties influencing rooting volume or depth, duration of crop uptake and soil biological activity (Stockdale et al. 2002). Conventional systems often rely on short-term supply of essential minerals in readily available forms. In contrast, organic farming cannot use readily available nutrients in the form of synthetic fertilizers, but rely on strategic long-term approach to build up soil fertility by enhancing the soil processes.

Since synthetic fertilizers are prohibited in organic farming systems, organic farming relies on the management of soil organic matter to enhance the chemical, biological and physical properties of the soil. The basic strategies to enhance soil fertility in organic systems are the effective recycling of on farm nutrients, returning plant and animal residues to the soil and application of permitted mineral nutrients (Knight et al. 2010). Organic matter can be applied to the soil either through direct inputs of organic matter via animal manures, compost or by adding live plant materials via green manure or by adding crop residue. Since nitrogen is the most essential soil nutrient, organic farmers tend to include legume crops for grain, forage and green manure in crop rotations (Zentner et al. 2004). Thus a potential strategy for organic crop production is to use crop rotations with soil nutrient building phases and cash crop phases where soil nutrients are depleted (Alteiri 1995). Legume crops are an essential component in organic crop rotations due to their ability to biologically fix atmospheric nitrogen. Atmospheric fixed N can be utilized by the legume crops for their requirements and in addition, they can provide nitrogen to subsequent crops in the rotation (Welty et al. 1988; Beckie and Brandt 1997).

The use of legume green manure crops is the predominant nutrient management strategy in organic systems in the Canadian prairies. Usually green manures are annual or perennial legume crops planted in the spring and incorporated into the soil during the summer. Green manures are terminated early in the growing season while still green and before seed production and either incorporated with tillage or left on the soil to decompose and provide a mulch. Early season termination is critical in the prairies in order to conserve soil moisture. Crop-fallow systems were formerly common in the prairies particularly in the dry region since moisture conservation is critical. However, due to erosion and soil depletion (Campbell et al. 1997) legume based partial fallow system were evaluated and promoted (Zentner et al. 2004). Accordingly, in organic systems, legume green manure crops have been used to replace the fallow. Enhanced soil organic C was found in a six-year study comparing four annual green manure legumes [black lentil, Tangier flatpea (*Lathyrus tingitanus* L.), chickling vetch (*Lathyrus sativus* L.) and field pea (*Pisum sativum* L.)] in rotation with wheat compared to the fallow-wheat rotation, but no difference found compared to the continuous wheat treatments (Biederbeck et al. 1998). Crop rotations with legume cash crops can provide some amount of soil N to the subsequent crop (Zentner et al. 2001). Annual legume crops such as pea (Biederbeck and Bouman 1994; Biederbeck et al. 1998; Lawley 2004), black lentil (Biederbeck and Bouman 1994; Biederbeck et al. 1998; Brandt 1999; Lawley 2004), chickling vetch (Biederbeck and Bouman 1994; Biederbeck et al. 1998; Lawley 2004), faba bean (*Vicia faba* L.) and annual alfalfa (*Medicago sativa* Leyss) (Townley-Smith et al. 1993) have been evaluated in the semi-arid regions. Field pea was also found to provide the greatest N benefit to the succeeding wheat crop compared to chickpea, dry bean and soybean (Przednowek et al. 2004). Of the annual legumes the most advantageous is therefore field pea (Biederback et al. 1996), chickling vetch (Biederback et al. 1996; Lawly 2004) and Indian head lentil (Lawly 2004). Even though field pea found to be the most productive, due to small seed size, lentil was found to be more economical to use as green manure in the Canadian prairies (Lawly 2004). Farmers in the Canadian prairies use annual, biennial or perennial legumes as green manure crops. Despite the benefits of perennial legumes they are not the most common choice due to the excess plant water use causing soil moisture depletion that can thereby reduce the yields of subsequent crops (Meyer 1987; Hesterman et al. 1992; Zentner et al. 1996;). Biennial yellow sweet clover (*Melilotus officinalis* L.) is the most widely grown green manure crops in organic farms in the prairies (Woodly et al. 2012).

Crop residues are also an essential component in managing soil fertility. Crop residues helps to retain moisture (Boehm and Anderson 1997), reduce erosion, and enhance nutrient cycling (Soon and Arshad 2002). Residues of temperate crops in general can contain 19-120 kg ha^{-1} of N (Mitchell et al. 2000). This organic N needs to be decomposed (mineralized) via soil microorganism to provide plant and microbial available N. The quality (C:N ratio) of the crop residues and the environmental factors determine the rate of mineralization (Lupwai et al. 2006). Having diverse crop rotations enables different amounts and quality of crop residues and subsequently enhanced microbial diversity (Bending et al. 2002). Crop residues with low C:N ratio have more rapid mineralization compared to those with a higher ratio (Kumar and Goh

2003). Legumes such as peas have greater decomposition and release minerals than cereals (Soon and Arshad 2002). Yet, rapid mineralization can cause depletion of soil organic matter (SOM). Therefore, crop rotations with different C:N ratio can help to provide nutrients as well as increase the SOM content.

2.10.3 Soil fertility in organic vs. conventional

Soil fertility in organic systems is generally thought to be high due to the high soil organic matter and N (Lockeretz et al. 1981; Reganold, 1988; Reganold et al. 1993; Teasdale et al. 2007) contents. Proponents of organic farming argue that the long-term practice of organic crop production can increase soil fertility in numerous ways. Soil organic matter is the principal component of maintaining soil fertility, and it is widely known that some organic systems have greater amounts of it due to the use of farmyard manure and green manure (Clark et al. 1998; Drinkwater et al. 1998; Liebig and Doran 1999; Mader et al. 2002). Many studies have found greater soil organic C (SOC) in organic systems (Pimental 2005; Teasdale 2007; Kirchman et al. 2007; Mondelaers et al. 2009). In the European organic systems, Clark et al. (1998) found that the C, P, K, Ca, and Mg inputs to the soils were higher in organic and low-input systems as a result of manure applications and cover crop incorporations. Higher levels of total and organic C, total N and soluble P have been reported for organic soils (Cavero et al. 1997, Clark et al. 1998; Poudel et al. 2002) compared to the conventional soils.

The timing of nutrients available from organic materials, particularly from green manures, are not often synchronized with the crop demand causing lower yields. Still, the beneficial effects of high soil organic matter can compensate for its low solubility due to its high water holding capacity and nutrient retention capacity (Van Bueren et al. 2002). Plant available P has been found to be the most limited soil nutrient on Canadian organic farms (Entz et al. 2001; Malhi et al. 2002). In a survey conducted on 44 farms in Saskatchewan it was found that all fields were deficient in P (Shirtliffe and Knight 2003). Mineral soil nitrogen was found to be in the range of 4-100 kg/ha) and either found to be deficient or optimal depending on the farming practices indicating it may not be a common problem in the region. In another study Entz et al (2001) identified that soil K levels to be sufficient in most situations, but the soil S can be insufficient, particularly in Gray and Dark Gray Luvisolic soils (Shirtliffe and Knight 2003). Returning crop residues alone cannot replenish the amount of nutrients exported with the marketed crop; hence, in the long run, essential nutrients can be depleted from soils. The mostly utilized strategy to alleviate nutrient deficiencies in the prairies is to include legume crops for grain, forage and as green manure in the rotations (Zentner et al. 2004). This strategy will only supply N to the soil in considerable amounts, but not P, K, S or other essential nutrients (Malhi et al. 2012).

Application of farmyard manure is not a common practice in most of the organic systems, of the Canadian prairies. In a survey Buhler (2005) identified that in Saskatchewan only seven out of 73 farms received farmyard manure in over the two year period of the study. Importantly, composted manure can supply N, P, K and S nutrients, which are generally lacking in soils (Brandt et al. 2007).

2.10.4 Soil health and improved soil biodiversity

Organically farmed soils are often found to have higher diversity and abundance of soil bacteria (Drinkwater et al. 1995; Mäder et al. 2002; Diepeningen et al. 2006), arbuscular mycorrhizal fungi (Oehl et al. 2003), nematodes (Mulder et al. 2003; van Diepeningen et al. 2006), earthworms (Mäder et al. 2002) and insects and arthropods (Drinkwater et al. 1995; Mäder et al. 2002; Asteraki et al. 2004) compared to conventionally managed soils. Furthermore, a higher microbial activity (Workneh et al. 1993; Mäder et al. 2002) and microbial biomass (Mäder et al. 2002; Mulder et al. 2003) have been found in organically managed soils. All these properties could directly or indirectly assist soil fertility over the long-term thereby increasing crop productivity.

2.11 Soils and weed population dynamics

Soil seedbank persistence, seedling establishment and interspecific interference are the key processes that determine annual weed population dynamics (Buhler 1999). These processes are controlled by the diverse climatic and biotic interactions. The diversity in soil properties in different cropping systems can therefore influence weed dynamics. Weed seed losses from the seedbank are incurred due to germination, predation, microbial invasion or decay. All these species-specific intrinsic factors and extrinsic factors such as soil biotic and abiotic environment can influence seed loss. Therefore, crop management practices such as tillage, soil fertilizers, cover crops and green manure crops that influence soil health and thereby weed dynamics (Buhler 1999).

Soil factors are also known to influence weed dynamics by altering crop–weed competition. Soil fertility improving practices can contribute to differences in species performances through the changes in spatial and temporal resource that supply soil nutrients and by residue mediated effects (Buhler 1999). Crops and weeds compete for growth resources such as soil nutrients, light and water. Plants either compete for resources by hindering the growth of another or they coexist due to niche separation with minimal competition for resources (Gause 1934; Chase and Leibold 2003; Silvertown 2004). According to the niche theory, plants segregate along niche axis (a gradient of resources) based on the requirements and modes of obtaining them (Silvertown 2004). Even though niche separation is believed to be the main driver for plant co-existence, direct evidence for niche separation and factors underlying niche separation is not well known (Silvertown 2004). However, the spatial and temporal heterogeneity in soil resources may contribute to niche separation and allow for plant species coexistence. The widespread understanding of soil resource partitioning of different chemical forms of N among co-occurring plant species (Miller and Bowman 2002; Finzi and Berthrong 2005; Pornon et al. 2007) and the diversity in microbial mediated plant resource uptake (Bever 1994; Bever et al. 1997; Van Der Heijden et al. 1998; Klironomos 2002; Reynolds et al. 2003) provide some insights to understand plant population dynamics related to soil resource dynamics. Niche separation may have relevance to plant species coexistence in agriculture as Smith et al. (2010) proposed the resource pool diversity hypothesis (RPDH) to explain the differences in crop weed competition in diverse cropping systems. According to the RPDH, crop-weed competition intensity in agroecosystems depends on the niche separation and resource partitioning among crop and the weed. Accordingly, the higher the diversity in soil resource pools, there is more niche separation reducing crop-weed competition for limited resources. The diversity in soil resource pools and their dynamics are hypothesized to reduce competition intensity among functionally different plant species. Thus, diverse cropping systems can enhance the diversity in resource pools; thereby, potentially reducing crop-weed competition (Smith et al. 2009).

The diversity in crop rotations may result in differences in soil quality and nutrient dynamics among cropping systems. Crop diversification affects soil physical, biological, and chemical properties that can alter weed growth and competitive ability (Liebman and Davis 2000). Diverse crop rotations affect the nature, quantity, and quality of crop residue due to differences in crop species and their management practices (Smith et al. 2010). The quantity and quality of crop residues directly influence the formation of soil organic matter (Jenkinson and Ladd 1981) as well as the availability and timing of nutrients via mineralization (Jarvis et al. 1996). Soil microbiological diversity, activity and biomass are also influenced by cropping intensity and diversity (Lupwayi et al. 1998, 1999). According to Smith et al. (2010), a gradient of soil resource pool diversity can be created with the crop diversification by using crops with different functionality. Diverse crop rotations will have species with contrasting functions such as legume versus non legume, broad leaf versus grass, annual versus perennial. Furthermore, cropping systems can differ in terms of the type and the amount of inputs being used including a tillage versus no-till, organic fertilizers versus synthetic fertilizers. In particular, organic systems with diverse crop rotations and organic fertilizer inputs can have more diverse soil resources, which thereby can result in reduced weed competition compared to less diverse conventional systems (Ryan et al. 2009). Other than a direct influence on crop-weed competition via soil resource mediation, soil management can influence crop-weed competition via microbial mediated growth reduction in weeds. However, there is high variability among organic systems in terms of crop management practices; and generalization may not be appropriate.

2.12 Multivariate analysis of plant community data

Multivariate statistical methods which involves simultaneous analysis of several response variables are important statistical techniques to investigate and summarize underlying trends in complex data (Legendre and Legendre 1998). Multivariate data are generated when more than one variable is measured on each sampling unit either in a survey or in an experimental unit (Kenkel et al. 2002). Most plant community analysis studies have biotic (species) data collected from each sampling unit giving a data matrix of (plots x species). In some instances, there can be both biotic and abiotic (environment) data collected from each unit giving a plots x species x environment data matrix. The objectives of analyzing such data in ecology are twofold: descriptive modeling which involves summarizing underlying data structures and predictive modeling which involves hypothesis testing (Jeffers 1988). With both approaches, data reduction to reduce the dimensions in the data matrix is the common feature of multivariate methods (Legendre and Legendre 1998).

A biotic data set typically has many zeros since many species are absent from most sampling units, making it difficult to use linear multivariate methods in the analysis (McCune et al. 2002). A linear multivariate model assumes a linear response of the species abundance to environmental gradients. Most community data do not follow linear response unless the environmental variables are measured for a narrow range. On the other hand, all biological entities tend to be most abundant around their optimum environmental requirements (McCune et al. 2002). Therefore, species response to environmental gradients are known to follow a Gaussian response in which it can be explained by a bell shaped curve with mean position on the environment gradient, standard deviation and a peak abundance (McCune et al. 2002). The most common multivariate techniques such as principal component analysis (PCA) and discriminant analysis assume a linear model while correspondence analysis (CA) assumes a nonlinear distribution.

2.12.1 Ordination for plant community analysis

Multivariate ordination and classification are the two main types of multivariate statistical methods utilized in plant community analysis. Ordination is used in ecology in order to describe species based on their abundance along environmental gradients. It allows the summarization of patterns of species composition. In these methods, multidimensional data space is represented as a set of mutually perpendicular (orthogonal) ordination axes (Kenkel et al. 2002). Ordination axes are considered latent variables or hypothetical variables that optimize the fit of the species abundance data to a particular linear or unimodal model. It describes how species abundance varies along environmental gradients (Ter Braak 1985, 1987). There are two types of ordination analysis including direct gradient (predictive), and indirect gradient (descriptive ordination) analysis. In a direct gradient analysis, sample units are positioned according to the measurements of the environmental factors in those sample units (species distribution constrained by environmental variables measured). In an indirect gradient analysis, sample units are positioned according to association among species (MacCune et al. 2002). In indirect gradient analysis, it is assumed that the ordination axis corresponds to underlying environmental factors indirectly measured by the sampled species data (Ter Braak and Prentice 1988). In direct gradient analysis, the ordination axis represents species variation constrained by environmental factors under consideration. Therefore, variation in species composition along such axis is attributed to the variation of the particular environmental factors used in the analysis.

Yet, in indirect gradient analysis, the ordination axis represents the gradient of species composition which is not bound by any particular environmental gradient, and therefore represents the total variation of the species composition. Direct gradient analysis is used to examine the relationship between two sets of variables (species data and environmental data) measured in the same sampling units. The objective of direct gradient analysis is to determine the extent to which the environmental data determines or predicts the biotic community and to understand the relative importance of variables predicting the community composition. In weed science, when the species abundance data are collected from individual experimental units and when each unit is subjected to particular experimental treatments, these treatments represent environmental variables in the analysis.

Out of different types indirect or direct ordination methods, the choice of a method depends on whether the data is linear or unimodal. Principal component analysis is a linear indirect ordination method while redundancy analysis is a linear direct ordination method. The non-linear methods or unimodal methods are the correspondence analysis (CA) and canonical correspondence analysis (CCA) where the latter is a direct ordination method. Weed species data displaying a unimodal response can be best analyzed by CCA and therefore it is the most frequently used method to describe weed communities affected by environmental variables (Kenkel et al. 2002). Leeson et al. (2000) and Dale at al. (1992) used CCA to correlate management practices to weed communities. However, for a narrow range of environmental gradients, a linear approach such as redundancy analysis can be appropriate.

2.12.2 Redundancy analysis

Redundancy analysis is the canonical or constrained form of PCA (Legendre and Legendre 1998). The objective of RDA is to model the association between a set of response variables (species abundance) and a given set of environmental variables. In RDA, the sampling unit locations in species space are restricted to be linear combinations of predictor variables or the environment variables (Ter Braak and Smilauer 2002). This method closely represents multiple linear regression analysis. Redundancy analysis is appropriate only when both species and environmental data are linear and when environmental data is used to predict species composition but not vice versa (Kenkel 2006). According to Ter Braak and Smilauer (2002), a gradient length of less than four species standard deviations is considered linear and greater than four is considered unimodal. When the data are unimodal the choice of method would be to use canonical correspondence analysis (CCA). Furthermore, the number of environmental variables should be lower than the number of sampling units and species (Dray et al. 2003). Redundancy analysis was the potential choice in weed sciences to find the relationship between agronomic treatments and weed composition (Thomas and Frick 1993; O'Donovan et al. 1997).

2.12.3 Principal response curves in plant community analysis

Ordination techniques such as canonical discriminant analysis (CDA), canonical correspondence analysis (CCA), and redundancy analysis (RA) are the most common multivariate constrained ordination techniques used to study the relationship between crop management and weed community composition (Derksen et al. 1993; Shrestha et al. 2002; Sossnoski et al. 2006; Moonen and Barberri 2004; Fried et al. 2008; Ryan et al. 2010). Most of these methods are used to study the cumulative effects of crop management on weed composition over a time period rather than temporal dynamics of the species composition. In long-term agronomic trials, understanding the long-term temporal changes in weed community composition associated with management practices is the main interest. Even though these above techniques are superior to univariate methods, these techniques are not sufficient to understand the temporal dynamics in plant communities as it is difficult to interpret temporal trends in the typical ordination. The principal response curve method (Van den Brink and Ter Braak 1999) was developed to overcome the difficulty of explaining cluttered bi-plots when many sampling time points and treatments displayed in one diagram without showing the directional change in time points. Earlier, RDA was the choice of method to analyze such experiments, but the interpretation of RDA diagrams becomes extremely difficult for time series data (Van den Brink and Ter Braak 1999). Furthermore, RDA will not provide trajectories or treatment effects and cannot be contrasted with a reference treatment time series. The PRC method has been utilized in ecotoxicology (Vand den Brink et al 2000) as well as in restoration ecology (Pakeman 2004; Vandvik et al. 2005; Palik and Kastendick 2010; Poulin et al. 2013). Therefore, the method principal response curve (PRC) can be used in weed science to overcome the limitations of commonly used ordination methods. Principal response curves are a variant of RDA for repeated observation designs. This method specifically allows the study of temporal dynamics of species composition. The PRC method enables to contrast time series of species composition of a treated or impacted site relative to a reference or a control treatment or site (Van den Brink and Ter

Braak 1999). Later, Van den Brink et al. (2009) proposed an additional approach to PRC by using a time point as a reference instead of a treatment time series previously used by Van den Brink and Ter Braak (1999). This allows contrasting trajectories or time series of all treatments of the experiment from a benchmark time point where treatments were initiated. This method is applicable when there is no particular control treatment and comparisons of all treatment time series are of interest. The model for the first PRC is given according to Van den Brink et al. (2003):

$$Y\ d(j)t_k = y0t_k + b_k\ c_{dt} + \sum d(j)t_k \qquad [1.1]$$

where $yd(r)t_k$ is the log-abundance of species k in replicate j of treatment d at time t, $y0t_k$ is the mean log-abundance of species k in time t in the control treatment (d = 0), cdt is the standardized canonical regression coefficients of the d^{th} treatment at time t, b_k is the weight of the kth species which is the proportional change of species(k) in treatment(d) and in year(t) relative to the species abundance in the treatment or the time point set as the reference or the control point. $\sum d(j)t_k$ is the error term with mean zero and variance σ_k. To obtain principal response curves, standardized canonical regression coefficients (c_{dt}), standard deviations of environmental variables (Sd) and total standard deviation in the species data (TAU) is obtained from the RDA output. PRC scores can be calculated using the following equation according to Van den Brink and Ter Braak (1999):

$$(TAU^*C_{dt})\ /Sd \qquad [1.2]$$

After obtaining the PRC scores they were graphed against the time for each treatment. Species weights b_k for the first axis were obtained from RDA and was tabled in a separate figure. Species weights were calculated using the following equation according to Van den Brink and Ter Braak (1999):

$$\exp\ (b_k{}^*C_{dt}) \qquad [1.3]$$

Which express the proportional change of species (k) in treatment (d) and year (t) relative to the year set as the reference or the control time point. The PRC results are shown in a diagram showing time in X axis and the first principal component of the variation in the Y axis.

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3.0 LONG-TERM WEED DYNAMICS AND CROP YIELDS UNDER DIVERSE CROP ROTATIONS IN ORGANIC AND CONVENTIONAL CROPPING SYSTEMS IN THE CANADIAN PRAIRIES

3.1 Abstract

Alternatives to conventional farming are becoming more popular worldwide as farmers seek to limit environmental impacts while improve crop productivity. Alternative cropping systems are gaining attention throughout the world due to the negative environmental effects of conventional tillage-based monoculture cropping systems on the sustainability of agro-ecosystems. Accordingly, in the Canadian prairies, traditional tillage-based crop-fallow systems have been largely replaced by no-till, reduced input systems or tillage-based organic systems, with both having more diversity in crop rotations than the traditional systems. However, the long-term effects of these systems on weed and yield parameters are not well known. A study was carried out using the data collected from the long-term alternative cropping systems (ACS) trial near Scott, Saskatchewan to understand weed and crop yield dynamics under diverse cropping systems in the prairies. Its goal was to examine how different crop input systems and rotations impact weed density, weed biomass and grain yields. The ACS trial was a four replicate split-split-plot design with three levels of inputs as high input (HIGH) systems that used tillage and inputs (pesticides and fertilizers) as required, reduced input systems (RED) that used no-till practices and site specific use of inputs and tillage-based organic (ORG) systems that used non-chemical pest control and nutrient management practices. The three levels of cropping diversity (rotations) were fallow-annual grains (LOW), diversified annual grains (DAG) and diversified annuals and perennials (DAP). Statistical analysis of the 18-year data revealed that the ORG systems had seven times and four times greater weed density, four times weed biomass and 32% and 35% lower crop yields than the RED and HIGH systems respectively. The RED and HIGH systems had similar crop yields and weed abundance. The LOW diversity rotation had the least weed abundance. The LOW and DAG rotations had similar yields and were greater than yields produced by the DAP rotation. All cropping systems showed an increase in weed abundance and crop yields over time, likely influenced by the concurrent increase in rainfall. This study revealed that eliminating tillage and reducing agrochemicals does not necessarily lead to reduced yield or increased weed abundance over time. However, totally eliminating agrochemicals does decrease

yield and increase weed abundance compared to conventional systems. It was also identified that increasing the diversity in crop rotations from a crop-fallow system does not improve crop yields or decrease weed abundance.

3.2 Introduction

Until relatively recently, farmers have responded to the challenge of feeding an ever-increasing world population by relying on practices that maximize crop production (e.g., intensive tillage, the use of monoculture, and application of fertilizers and pesticides) while overlooking long-term sustainability issues. Although these conventional systems produce greater yields (Tilman et al. 2001), they cause considerable environmental harm, including soil degradation (Bowman 1999; Campbell 2000), destruction of soil organic matter (Janzen 2001), emission of greenhouse gases (Dusenbury et al. 2008; Guo et al. 2010) and negative effects on natural ecosystems due to pesticides and fertilizers (Carpenter et al. 1998; Tilman et al. 2001).

Due to an increasing awareness of these negative impacts of conventional practices, farmers throughout the world have adopted no-tillage (no-till) systems with greater crop diversity in crop rotations. Furthermore, organic farming is also considered a viable alternative to conventional high and reduced input cropping systems. Therefore, reducing or eliminating external inputs (i.e., fertilizers and pesticides) and or tillage while increasing crop diversity and intensity is believed to be a key strategy for achieving sustainability in crop production.

Over the years, crop production in the Canadian prairies has been transformed from tillage-based, less intensified, wheat-fallow monoculture systems to now being either reduced-input no-till systems or tillage based organic systems, both having diverse crop rotations (Lafond et al. 1992, 1993; Dhuyvetter et al. 1996; Zentner 2002). Until the 1980s, annual cropping followed a crop-fallow or crop-crop-fallow rotation, with spring wheat (*Triticum aestivum* L.) as the main crop (Campbell et al. 2002). Despite increased productivity and economic gains in the dry regions, the long-term production of low-diversity crop rotations with fallow and use of intensive tillage resulted in substantial loss of topsoil due to wind and water erosion, deterioration of the quantity and quality of organic matter, increased soil salinization and greenhouse gas emissions (Campbell and Souster 1982; Janzen 2001). At present, due to the advancements in seeding and herbicide technologies, the adoption of conservation tillage (no-till or minimum tillage) has become widespread in the prairies (Zentner et al. 2002). The advantage of moisture conservation from no-till has eliminated the requirement of a fallow and allowed for more intensification and diversification of cropping systems in the prairies by using pulses, oilseed crops, legume green manure crops and perennial forages in the rotations (Peterson et al. 1993; Zentner et al. 2001, Entz et al. 2002; Zentner et al. 2002). Furthermore, organic farming is also increasingly practiced in Canada, due to an awareness of the environmental impacts of agro-chemicals, the rise of input costs in conventional farming, and the growing demand for organic products (Ngouajio and McGiffen 2000; Entz et al. 2001).

These transformations in cropping practices occurred in the prairies are believed to greatly benefit soil productivity and environmental sustainability but they also alter weed dynamics and crop yields. The impacts of tillage and crop rotations on weed abundance and composition have been widely studied (Buhler et al. 1994; McCloskey et al. 1996). Tillage intensity can affect weed emergence, seed production, vertical distribution, and weed seedbank densities in arable lands (Buhler 1995). No-till systems often have greater weed seedbank populations than moldboard plowed systems (Feldman et al. 1997; Barberi and Locascio 2001; Menalled et al. 2001). Similarly, crop rotations influence weed seed density and composition, both in the soil seedbank (Buhler 1999; Buhler et al. 2001; Cardina et al. 2002) and above ground (Blackshaw et al. 2001; Manley et al. 2002). Liebman and Dyck, (1993) reviewed 29 crop rotation studies and found that in most cases, both above- and below-ground weed density were markedly lower in rotations compared to their particular monoculture. However, crop-fallow systems have often been found to have less weed abundance than continuous cropping systems (Derksen et al. 1994). Therefore, although diverse crop rotations with conservation tillage are preferred for long-term sustainability, they can have conflicting effects on weed abundance and crop yields compared to the conventional tillage-based, low diversity fallow systems. Furthermore, organic systems have also been found to have greater weed abundance and lower crop yields compared to the conventional systems (Entz et al. 2001; Ryan et al. 2004; Posner et al. 2008)

Despite the enormous amount of empirical knowledge about the effects of cropping practices on weed dynamics, most studies have been limited to the individual effects of tillage, crop rotation, or fertilizers on weed abundance or weed composition. Less understood is whether these negative effects of conservation tillage on weed abundance can be overcome by better crop rotations or managing inputs. Diverse cropping systems have contrasting elements in terms of land preparation, weed control, soil fertility management, and crop diversity, and each of these elements can have different impacts on weed population dynamics (Menalled et al. 2001; Derksen et al. 2002) and grain yields. Hence, the reductionist approach of comparing individual crop management practices is not sufficient. There is a lack of understanding of the interactions between various input systems and crop diversity levels on the long-term weed dynamics and crop yields. Specifically, only few studies have examined weed abundance in long-term organic versus conventional cropping systems (Hiltbrunner et al. 2008; Ryan et al. 2010). Although some studies exist, the effect of cropping systems on weed dynamics is difficult to generalize across regions due to climatic and geographical variability. Therefore, this study attempts to understand the long-term impact of contrasting cropping systems in the Canadian prairies using a long-term (18 year) alternative cropping systems study (ACS) in Scott, Saskatchewan, Canada. The ACS has nine contrasting cropping systems with three levels of inputs (high, reduced and organic) and three levels of crop rotations (low diversity, annual grains, and annuals and perennials). The approach is to use a historical data analysis to answer three research questions: (1) Can tillage and the use of agro-chemicals be reduced without a long-term increase in weed abundance or decrease in crop yields in conventional systems? (2) Do the most diverse crop rotations have the least weed abundance and greater crop yields compared to the least diverse rotations over a long period of time? and (3) Will weed abundance increase over time in organic systems and thus decrease crop yields over time?

Statistical tools used to analyze long-term studies vary, and therefore conclusions can be subjective depending on the tools and methods used. Ideally, longitudinal analysis of long-term changes in weed dynamics and crop yields could provide more insights than the conventional point estimations as other influences on weed dynamics besides cropping systems could be considered, such as short and long-term weather conditions and patterns. Most of the long-term crop rotation experiments were typically analyzed using ANOVA with MIXED effect models which is a static approach (either look at individual years or mean of all years). These static approaches do not consider environment by treatment interactions present in long-term studies (Piepho et al. 2003). Random fluctuations in environmental conditions other than management practices can influence weed dynamics on top of the crop management practices in a given time point (Derksen et al. 1993). Ideally, longitudinal analysis of the long-term changes in weed dynamics and crop yields could provide more insights than the conventional point estimations. Therefore, this study attempt to use a combination of a static and dynamic statistical analysis approach using a fairly novel method to agronomy discipline known as random spline coefficient models (Verbyla et al. 1999; Rice and Wu 2001).

3.3 Materials and Methods

3.3.1 Site description and experimental design

The ACS trial was a long-term cropping systems study (1994-2012) established near Scott, Saskatchewan (52° 22'; 108° 50', elevation = 713 meters). It was in the Dark Brown soil zone between the semi-arid region to the south and the sub-humid region to the north. The details of the design and management of the ACS trial have been explained by Brandt et al. (2010); therefore, only the materials and methods relevant to our study are presented here.

The ACS trial consisted of two main treatments, systems (inputs) and crop diversity (rotations), with three levels under each treatment. It was a four replicate split-split plot design, with main plot treatments consisting of three levels of inputs and sub-plots consisting of three levels of crop rotations (Figure 3.1). Each crop rotation had six crop phases, with all crop phases occurring in a single year. The experimental site covered 16 (ha), with the main plots measuring 76.8 m by 140 m, sub-plots measuring 76.8 m by 40 m, and cropping phase plots measuring 12.8 m by 40 m.

The three input levels included the following: (1) organic systems (ORG), which used tillage and non-chemical pest control and nutrient management strategies; (2) reduced input systems (RED), which used no-till practices and integrated long-term management of pests and nutrients with limited use of chemicals to supplement other management practices; and (3) high input systems (HIGH), which used tillage along with pesticides and fertilizers “as required,” according to conventional recommendations associated with pest thresholds and soil tests (Brandt et al. 2010).

Crop rotations had three levels of crop diversity in each system with the crop rotations differing between the systems to reflect common crops and practices for each system. The three crop diversity levels were as follows: (1) low diversity rotations (LOW), which consisted of fallow and annual grains rotations; (2) diversified annual grains rotation (DAG), which consisted of cereal, oilseed and pulse crops, and (3) diversified annuals and perennials (DAP) rotation, which used a mix of grain crops and a three-year perennial forage crop. The crop phases in each cropping system are summarized in Table 3.1.

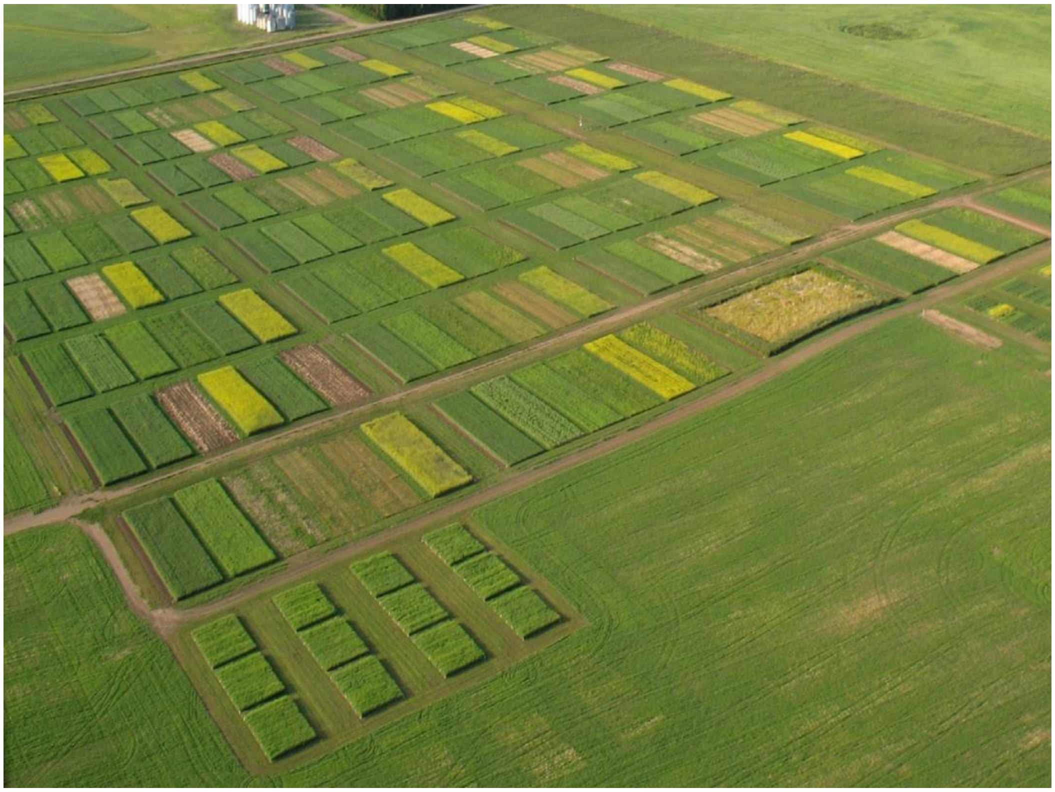

Figure 3.1. Aerial view of the long-term alternative cropping systems study (Photograph provided by Stu Brandt)

After the first 6 years of the study, oriental mustard (*Brassica juncea* L.) was substituted for canola in all ORG systems, since oilseed canola was no longer allowed for organic certification. Due to poor yields, fall rye (*Secale cereal* L.) was substituted with soft white spring wheat in the RED and HIGH diversified annual grain rotations. During the first six years of the study, the forage sequence was tame oat (*Avena sativa* L.) under-seeded to brome grass (*Bromus inermis* Leyss.) and alfalfa (*Medicago sativa* L.), followed by two years of brome and alfalfa hay. However, due to poor establishment of brome and alfalfa after the first six-year cycle, alfalfa was seeded alone without a companion cereal crop and left in place for three years. All crops were spring seeded except fall rye, which was seeded in September (Brandt et al. 2010).

3.3.2 Tillage

In HIGH and ORG systems, fall tillage was practiced every year between crop harvest in September and soil freeze up in November. Due to the intensive use of tillage it was not practiced after the completion of the second cycle. In RED input systems, tillage was rarely done; however, it was used in the RED-DAP system to terminate alfalfa in some years. Fall application of phenoxy herbicides (2,4-D or MCPA) was typically used for fall weed control in RED systems. Summer fallow tillage was used with the summer fallow and green fallow phases of the ORG-LOW and HIGH-LOW diversity systems. Organic green fallow used half of the tillage practices compared to conventionally tilled high input fallow. Spring pre-planting tillage was done for weed control and seed-bed preparation and typically consisted of one to two operations with a sweep-type cultivator followed by harrowing or harrow-packing. With RED input systems, herbicides were applied before planting to control weeds.

3.3.3 Crop establishment

Crops in the HIGH and RED systems were generally sown earlier than crops in the ORG systems, because organic growers usually practice late seeding to control weeds prior to planting. Crops that benefit most from early seeding such as canola and pea were sown first, while those that are less affected by late sowing, such as wheat and forages, were planted last. A detailed explanation of the planting pattern is provided in Brandt et al. (2010). Initially, seeding of all crops was done with a 20-cm row space hoe-press drill. During the later years, the HIGH and RED systems were seeded using a 25-cm row space drill, and the ORG systems were seeded using a 15-cm row space double disc press drill. In the HIGH and RED systems, wider inter-row space was needed to avoid plugging with crop residues, while the narrower inter-row space in the ORG systems were used to improve crop competition with weeds. Crops were sown at recommended rates in HIGH input systems and at 33% higher rates in the ORG and RED systems to improve crop competition with weeds.

Table 3.1. Crop phases of all cropping systems in the Alternative Cropping Systems trial near Scott, SK.

Input[a]	Rotation[b]	Crop phases
HIGH	LOW	Fallow-Wheat-Wheat-Fallow-Canola-Wheat
	DAG	Canola-Fall Rye-Pea-Barley-Flax-Wheat
	DAP	Canola-Wheat-Barley-Alfalfa-Alfalfa-Alfalfa
RED	LOW	GM-Wheat-Wheat-Fallow-Canola-Wheat
	DAG	Canola-Fall Rye-Pea-Barley-Flax-Wheat
	DAP	Canola-Wheat-Barley-Alfalfa-Alfalfa-Alfalfa
ORG	LOW	GM-Wheat-Wheat-GM-Mustard-Wheat
	DAG	GM-Wheat-Pea-Barley-GM-Mustard
	DAP	Mustard-Wheat-Barley-Alfalfa-Alfalfa-Alfalfa

[a] HIGH = conventional tillage with high inputs (i.e., pesticides and fertilizers, based on conventional recommendations); RED = no-till with reduced inputs; ORG = organic (non-chemical pest control and nutrient management); [b] LOW = fallow-annual grains; DAG = diversified annual grains; DAP = diversified annuals and perennials, GM = green manure fallow

3.3.4 Fertilizer and nutrient management practices

Urea-based nitrogen was applied at or before seeding based on soil test recommendations. The same rate was applied to all treatment plots in the HIGH systems, while in the RED systems, the rate applied in each plot was based on the soil test for that specific plot. This usually resulted in less fertilizer being applied to the LOW diversity rotations. Fertilizer phosphate was applied to RED and HIGH input systems, with the seed at constant rates (averaging 10.8 kg ha^{-1} of P). Recommended chemical seed treatments were used to seed in HIGH and RED systems. Rhizobial inoculants were used for nitrogen-fixing legumes when used for green fallow, grain, or forage crops and were applied to seed in all input systems. To provide some of the crop's phosphorus requirements, a commercially available *Penicillium bilaii* formulation was applied as a seed treatment on ORG and RED crops. At the end of each six-year cycle, composted manure was added to the RED-DAP and ORG-DAP systems to replace the nitrogen that would have been available had the forages and barley grown in these systems been fed to feeder cattle and the manure spread back on the land. The composted manure was applied and incorporated with tillage between the last forage phase and the subsequent grain phase. The details of the nutrient status in the ACS study can be found in Malhi et al. (2009).

3.3.5 Weed control

In-crop weed control in HIGH systems used recommended herbicides at recommended rates based on weed populations. In the RED systems, herbicides were only applied if weed thresholds were exceeded. Thresholds were based on published local guidelines (Saskatchewan Agriculture 1998) and varied depending on the crop, weed, and climatic conditions. Where the threshold was a range, the lower threshold number was used when the risk of yield loss was high, and the higher threshold number was used where the risk of yield loss was low. For ORG systems, in-crop harrowing was typically done for cereals and peas, but not for small seeded crops like mustard and alfalfa.

3.3.6 Data collection

When grain crops reached physiological maturity and forage crops reached the harvest stage, all plant biomass were removed at the soil surface from two areas per plot, each measuring 0.25 m^2. Biomass were separated into two groups: weeds and crop biomass, and both were dried at 100°C for 24 hours to provide an estimate of crop and weed dry biomass. All grains were harvested at physiological maturity. Grain yield was determined by harvesting a 2-m by 40-m strip from each plot, then drying cleaning and weighing the entire grain sample.

3.3.7 Data analysis

Residual weed biomass, weed density, and crop yield data collected from 1995 to 2012 in all crop phases were subjected to univariate statistical analysis. Weed density and weed biomass data for each year from the six crop phases were averaged for the analysis, while grain yield data for all crop phases excluding the green manure phases were averaged together. Average weed density, weed biomass and grain yields for all crop phases in each year were considered to determine the overall effect of crop rotation on weed abundance and crop yields than on the individual crop phases.

Initial data analysis with a linear mixed model confirmed the lack of fit of the model to the data due to non-linearity in the data. Due to the high variability in the response variables over time in this study, modeling a linear relationship with time was not possible. Hence, we used a random spline coefficient model (Verbyla et al. 1999; Rice and Wu 2001) to analyze all the variables. A random spline coefficient model is a semi-parametric model that has both parametric and nonparametric components (Verbyla et al. 1999). In this method, modeling the response variables as a random spline function of time for each individual treatment or group of treatments was carried out. This approach allows for subject specific covariances in long-term experiments (Fan and Zhang 2008). Using this method, response variables were modeled as a random spline function of time for each individual treatment or group of treatments. Weed biomass and weed density data were log transformed before the analysis. The data were analyzed using the GLIMMIX procedure in SAS 9.3 (SAS Institute Inc. 2011) assuming a normal Gaussian distribution (SAS Institute Inc. 2009). An example of the SAS code used to analyze the data is provided in Annex A.

All data collected over the 18 years were analyzed as a single time series (time as a continuous variable) to identify trends in the measured parameters. Input, crop rotation, time, and the interaction of input and rotation were considered fixed effects. Replication and its interaction with inputs were considered random. A repeated measures analysis was conducted, where replicate (block) was considered as the subject to model the autocorrelation function over time. The following competing random spline coefficient models were considered: individual treatment-specific (i.e., nine treatment combinations), input-level, or rotation-level; depending on the lowest AIC values, the best model was selected. For the weed density and weed biomass data, the covariances modelled by input level were selected as the final model while for yield data, the covariances modeled by crop rotation found to be the best fit of the model to the data. Differences in spline coefficients among treatments were tested using orthogonal contrast. Means were declared significantly different by using Tukey's honestly significant difference test at $P < 0.05$, and back-transformed means were displayed. Furthermore, linear regression analysis was carried out for yield with total seasonal rainfall, weed biomass, weed density and was declared significant at $P < 0.05$.

3.4. Results

3.4.1 Rainfall and growing conditions

The years between 1998 and 2004 were dry, with the total seasonal rainfall (April-September) below the long-term average of 261 mm (Figure 3.2A). The year 1998 was the driest, receiving only 148 mm of rainfall. However, despite year-to-year fluctuations, a gradual increase of average rainfall can be observed, particularly, from 1998 to 2012, where analysis of rainfall over time indicated a significant correlation ($P < 0.05$) between rainfall and time. In addition, seasonal maximum temperatures fluctuated from the long-term averages. The summers of 2004 and 2005 were fairly cool (Figure 3.2B), and the summers of 1998 and 2001 were hotter than the average.

3.4.2 Weed density

Input systems and crop rotations differed in mean weed densities over the 18 years; however, no interaction between input levels and crop rotations were identified (Table 3.2). Organic systems had seven times greater weed density compared to the RED systems and four times greater weed density compared to the HIGH systems (Figure 3.3A). There was no statistical difference between HIGH and RED systems for weed density (Figure 3.3A). This indicates that eliminating tillage and reducing herbicides did not increase overall weed abundance. Among crop rotations, the DAP rotation had the greatest weed density, which was two times greater than the weed density in the LOW diversity rotation (Figure 3.3B).

Weed densities varied throughout the years (Figure 3.4). The RED and HIGH input systems showed significantly high variability over time, but the ORG systems showed comparatively less variability according to covariance parameters (Table 3.2). Further, ORG systems showed relatively constant high weed density in all years, which was also reflected in high overall mean weed density. Despite the variability, all systems showed an increasing trend over the time. Except for RED systems, all the other systems showed an approximate linear increase in weed density over time (Figure 3.4). A nonlinear trend was identified in the RED systems, with a decrease in weed abundance in most years during the second cycle (2002-2008). All three input systems had a more than threefold increase in weed density from rotation cycle one the rotation cycle three (data not shown). This overall increase in weed density in all systems may be due to the increasing trend in rainfall throughout the 18-year period (Figure 3.2A). A similar association has been observed in the Glenlea long-term crop rotation study in Manitoba (Entz et al. 2014).

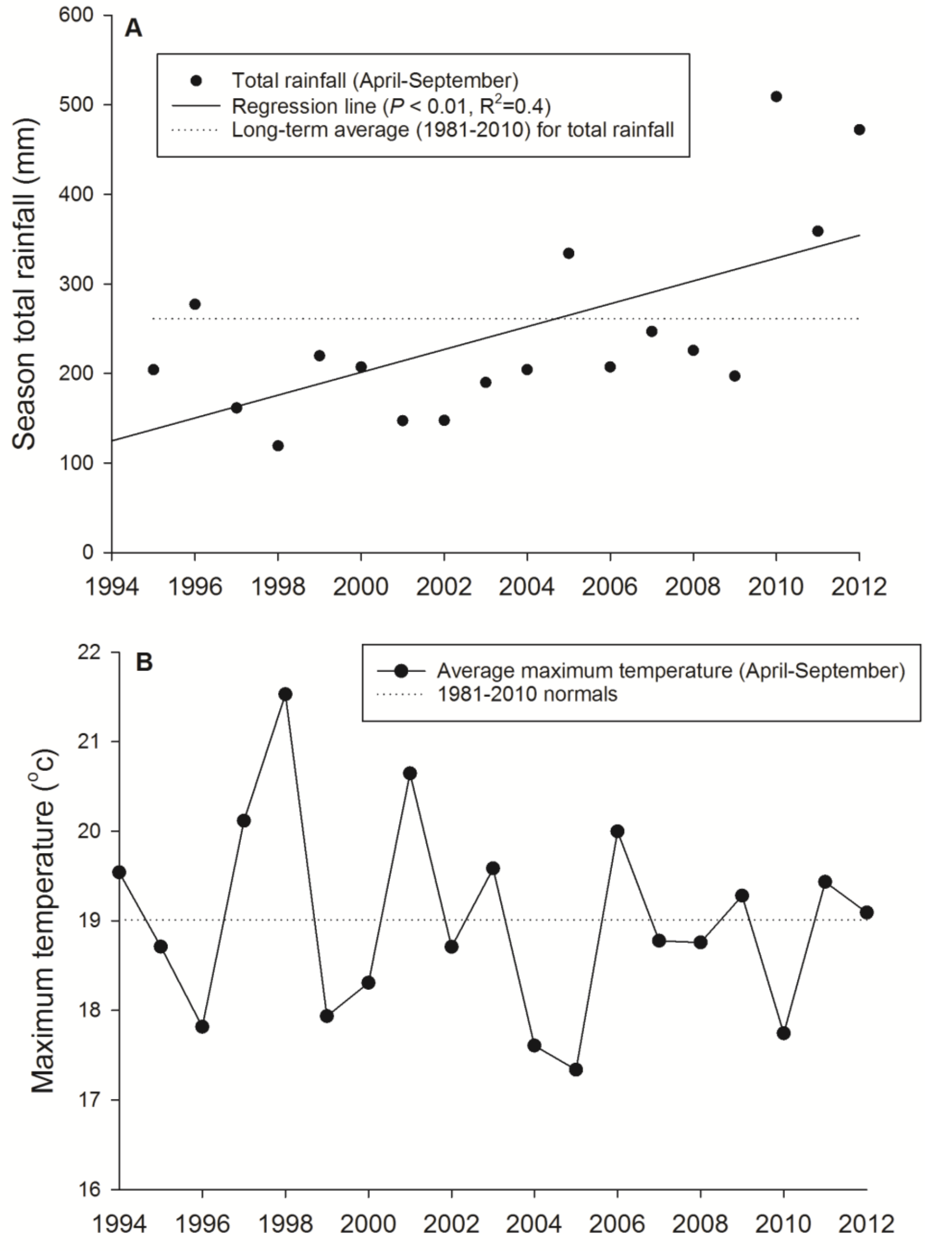

Figure 3.2. Crop growing season (April-September) rainfall (A) and maximum temperature (B). The dotted lines indicate the long-term season normal rainfall and temperature at the ACS site at Scott, Saskatchewan, Canada.

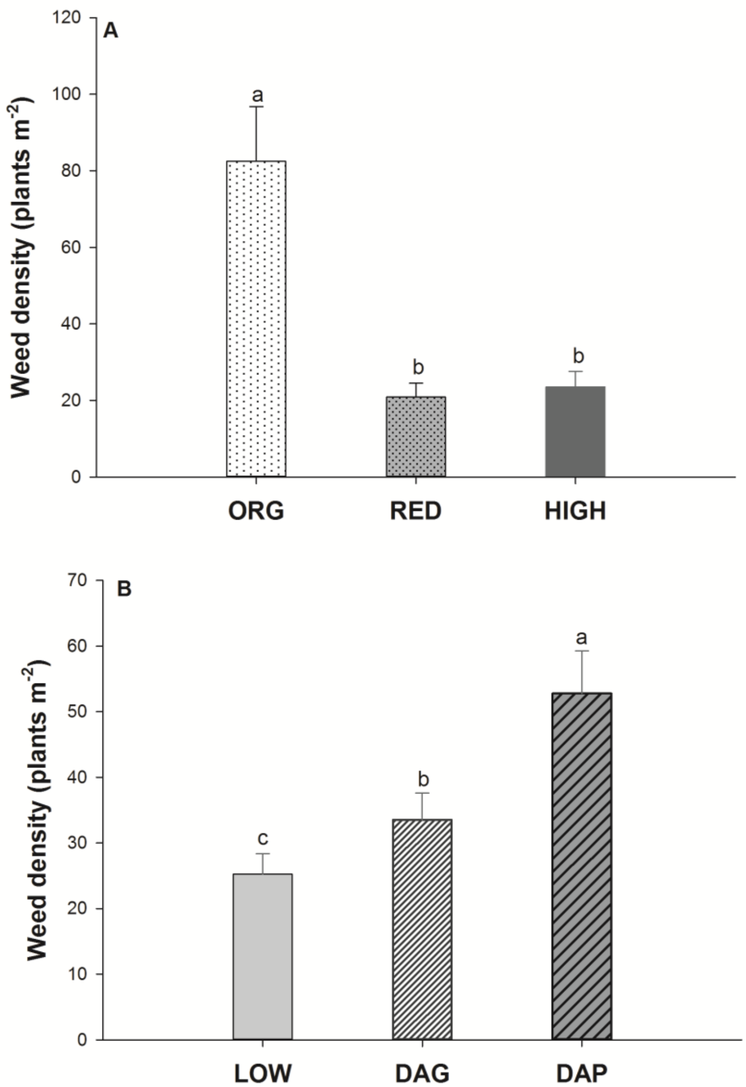

Figure 3.3. Mean residual weed densities (averaged across 18 years) affected by input (A) and rotation (B) assessed in ACS at Scott. Error bars indicate standard errors of the lsmeans. Comparisons made between treatments with different letters indicate a significant difference at Tukey's Honestly Significant Difference P < 0.05.

Table 3.2. Probability values for treatment means and covariance parameters for weed biomass, grain yield, and weed density at the ACS in Scott, SK.

Source of variance	Weed density±	Weed biomass±	Yield
Time	<0.0001	0.05	<0.0001
Input	<0.0001	0.0003	<0.0001
Rotation	<0.0001	0.02	0.02
Input-by-Rotation	0.16	0.04	0.17
Covariance parameters			
ORG	NE	NA	NA
RED	0.09	NA	NA
HIGH	0.08	NA	NA
DAG	NA	0.04	NE
DAP	NA	0.13	0.07
LOW	NA	0.05	NE
Contrast of covariance parameters			
ORG vs. RED	NE	NE	NE
ORG vs. HIGH	NE	NE	NE
RED vs. HIGH	NE	NE	NE
ORG vs. Non-organic	NE	NE	NE
DAG vs. LOW	NE	NE	NE
DAP vs. LOW	NE	0.05	NE
DAG vs. DAP	NE	NE	NE

± Data log transformed for analysis

NE = cannot estimate, NA = covariance parameters were not estimated

ORG = organic (non-chemical pest control and nutrient management); RED = no-till with reduced inputs (pesticides and fertilizers); HIGH = conventional tillage with high inputs (based on conventional recommendations); DAG = diversified annual grains; DAP = diversified annuals and perennials; LOW = fallow-annual grains

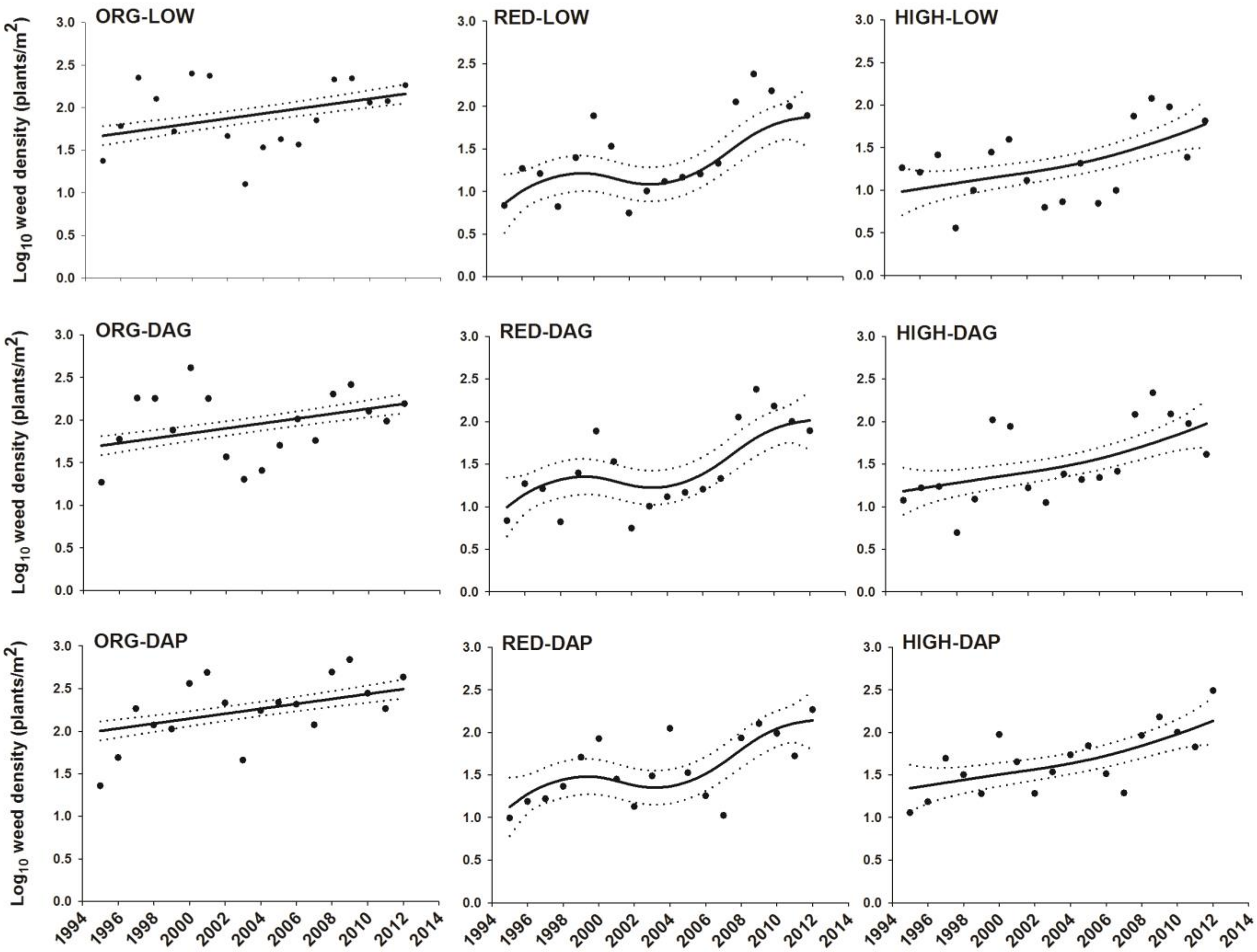

Figure 3.4. Eighteen-year trend in weed density assessed in ACS at Scott. Black circles represent the observed mean weed density in $\log_{10}$ scale for a particular year. The solid lines represent the linear/nonlinear predictions of weed density over time. Dotted lines represent the upper and lower 95% prediction interval.

3.4.3 Weed biomass

Mean weed biomass was affected by the input-by-rotation interaction (Table 3.2). The lowest weed biomass was observed in the fallow-grains rotations (LOW) in the RED and HIGH systems (Figure 3.5). The RED systems had one green manure fallow and one chemical fallow phase, while HIGH systems had two tillage fallow periods. Despite these differences, these systems had similar weed biomass. Therefore, having a green manure fallow phase in RED systems was found to have no negative effect on weed control compared to having a tillage-fallow in HIGH systems. However, comparing crop rotations across input levels may not be appropriate due to the contrasting differences in input levels. In DAP rotations in all systems, weed density was high but weed biomass was intermediate. Hence, differences in weed densities among cropping systems were not reflected in differences in weed biomass. Within RED and HIGH systems, the weed biomass in DAP rotations was similar to the biomass in DAG rotations. Weed biomass was four times greater in all ORG rotations compared to RED and HIGH rotations.

Crop rotations had high variability in weed biomass over time. According to covariance parameters, DAG and LOW diversity rotations showed significant variability over time (Table 3.2, Figure 3.6). However, based on the contrast of covariance parameters, the variance did not differ between DAG and LOW rotations (Table 3.2). A similar pattern was observed in both rotations as weed biomass tended to decrease from 1995 to 2005 and then increase from 2005 to 2012. The LOW diversity rotation was significantly different from the DAP rotation in terms of variability (Table 3.2). Despite short-term variability, weed biomass showed a curvilinear increase over the time within cropping systems. The continuous increase in weed biomass, particularly in the two conventional cropping systems (HIGH and RED), suggests that despite the annual use of herbicides, weeds were not completely controlled.

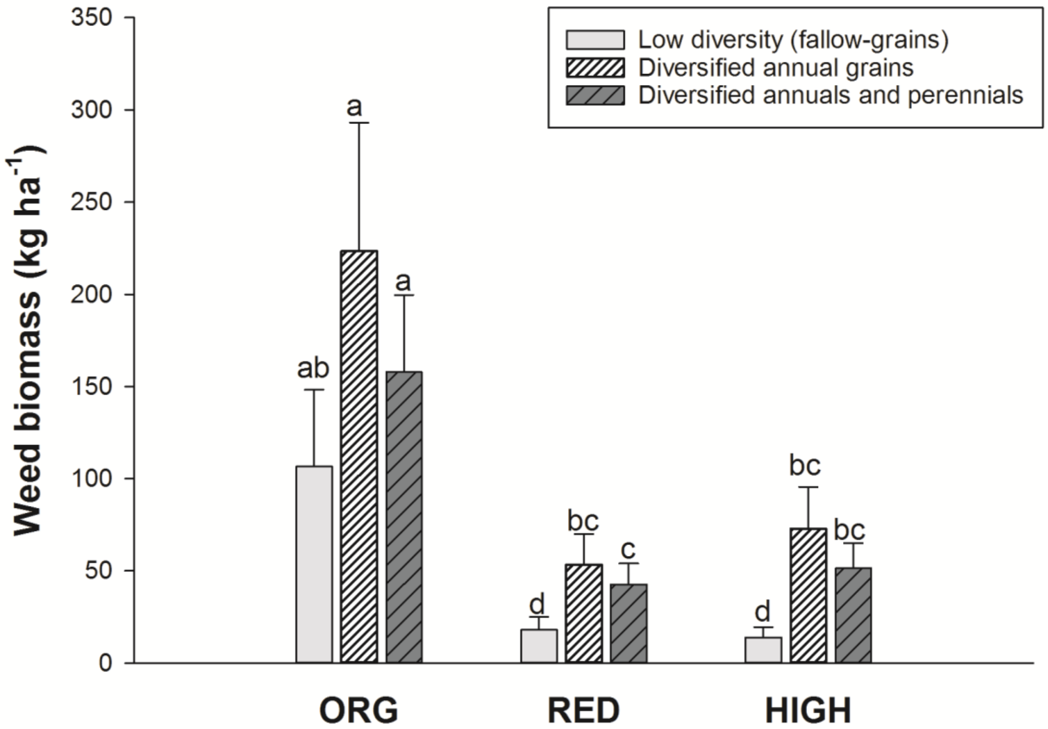

Figure 3.5 Mean residual weed biomass (averaged across 18 years) affected by input system and crop rotation assessed in ACS at Scott. Error bars indicate standard errors of the lsmeans. Comparisons made between treatments with different letters indicate a significant difference at Tukey's Honestly Significant Difference P < 0.05.

3.4.4 Grain Yield

Input systems and crop rotations had significant effects on crop yields (Table 3.2). The ORG systems had the lowest grain yield, which were 32% and 35% lower than the yields from the RED and HIGH systems, respectively (Figure 3.7A). The RED and HIGH systems had similar grain yields, suggesting that reducing agrochemicals and eliminating tillage (as was done in the RED systems) does not affect grain yields. Among crop rotations, the DAP rotation had the lowest yield and was 54% of the LOW rotation and was 50% lower than the DAG rotation (Figure 3.7B).

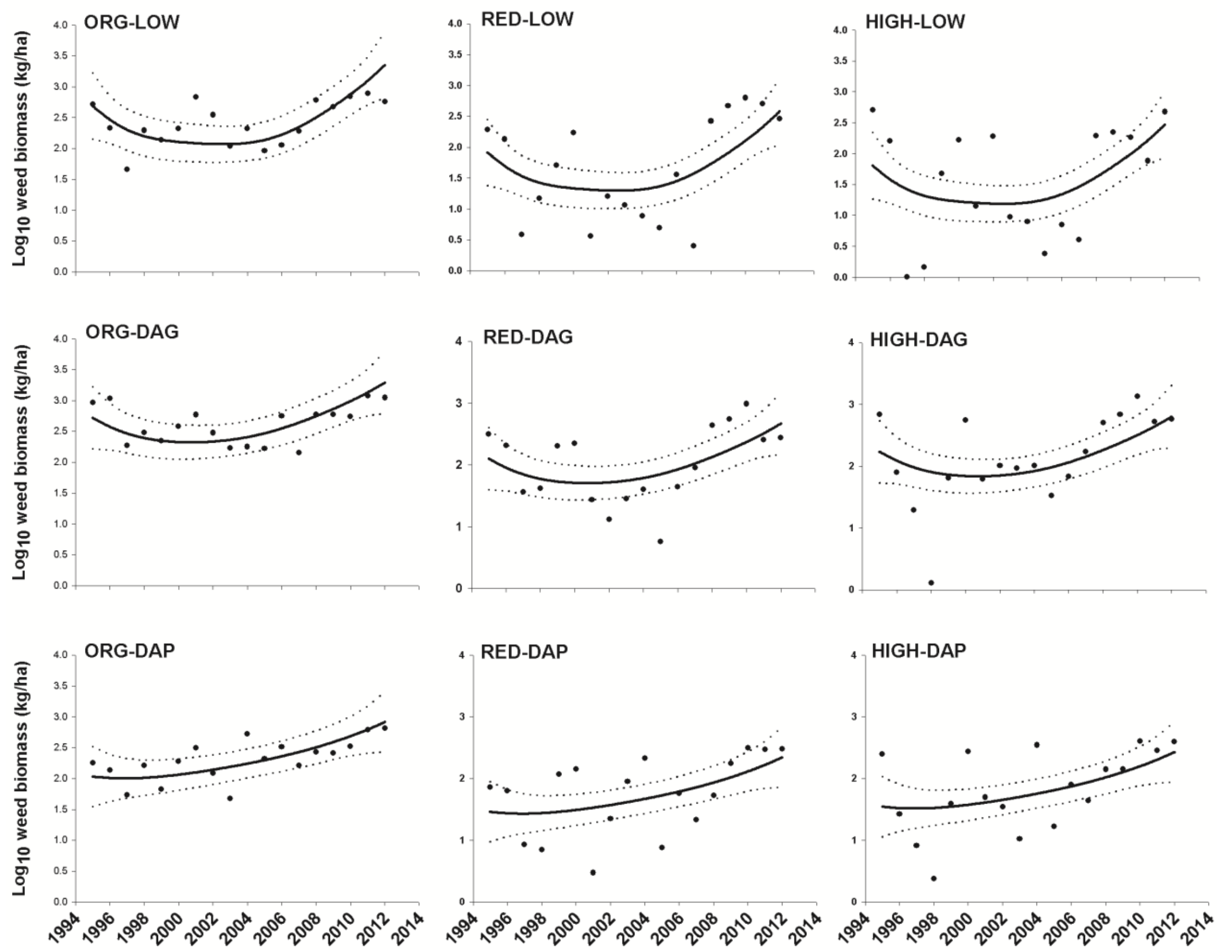

Figure 3.6. Eighteen-year trend in weed biomass assessed in ACS at Scott. Black circles represent observed mean density in log_{10} scale for a particular year. The solid line represents the linear/nonlinear prediction of weed biomass over time. Dotted lines represent the 95% prediction intervals.

Despite the differences in mean crop yields, cropping systems showed an increase in yield over time, with the exception of reduced yields in the second crop rotation cycle, particularly between the years 2000 and 2003 (Figure 3.8). This period was severely dry during the growing season (Figure 3.2A), which severely limited yields (Figure 3.8). Interestingly, although the overall grain yield was low, the ORG systems yields increased with time.

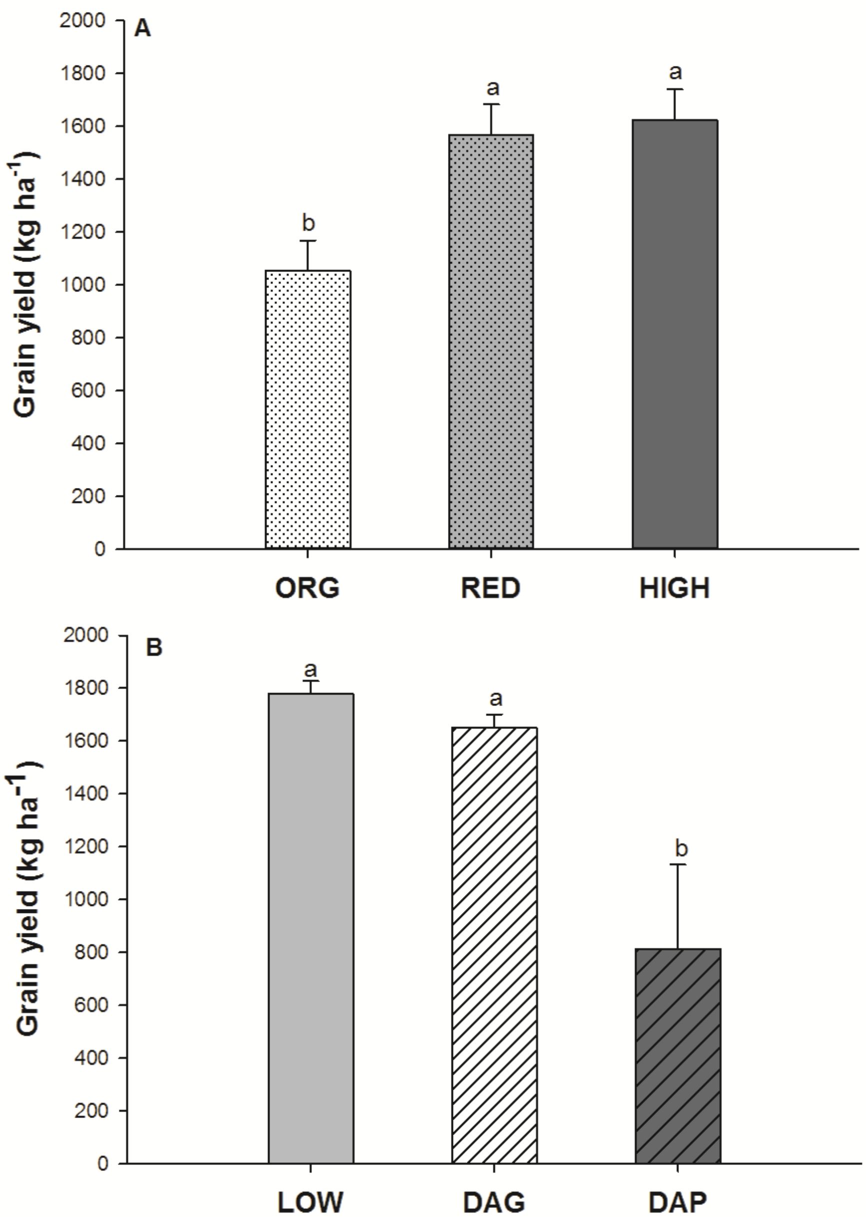

Figure 3.7. Mean grain yield (averaged across 18 years) affected by input system (A) and crop rotation (B) assessed in ACS at Scott. Error bars indicate standard errors of the lsmeans. Comparisons made between treatments with different letters indicate a significant difference at Tukey's honestly significant difference *P* < 0.05.

This increase in yield over time despite an increase in weed density and biomass suggests that an increase in weed abundance does not necessarily reduce crop yields. Accordingly, correlation analysis showed that there was a very weak relationship (Appendix B) between weed density and weed biomass with grain yield. However, grain yield was positively associated ($P < 0.001$) with increasing rainfall (Appendix B), suggesting that the increase in rainfall was partly responsible for the increase in grain yields over time.

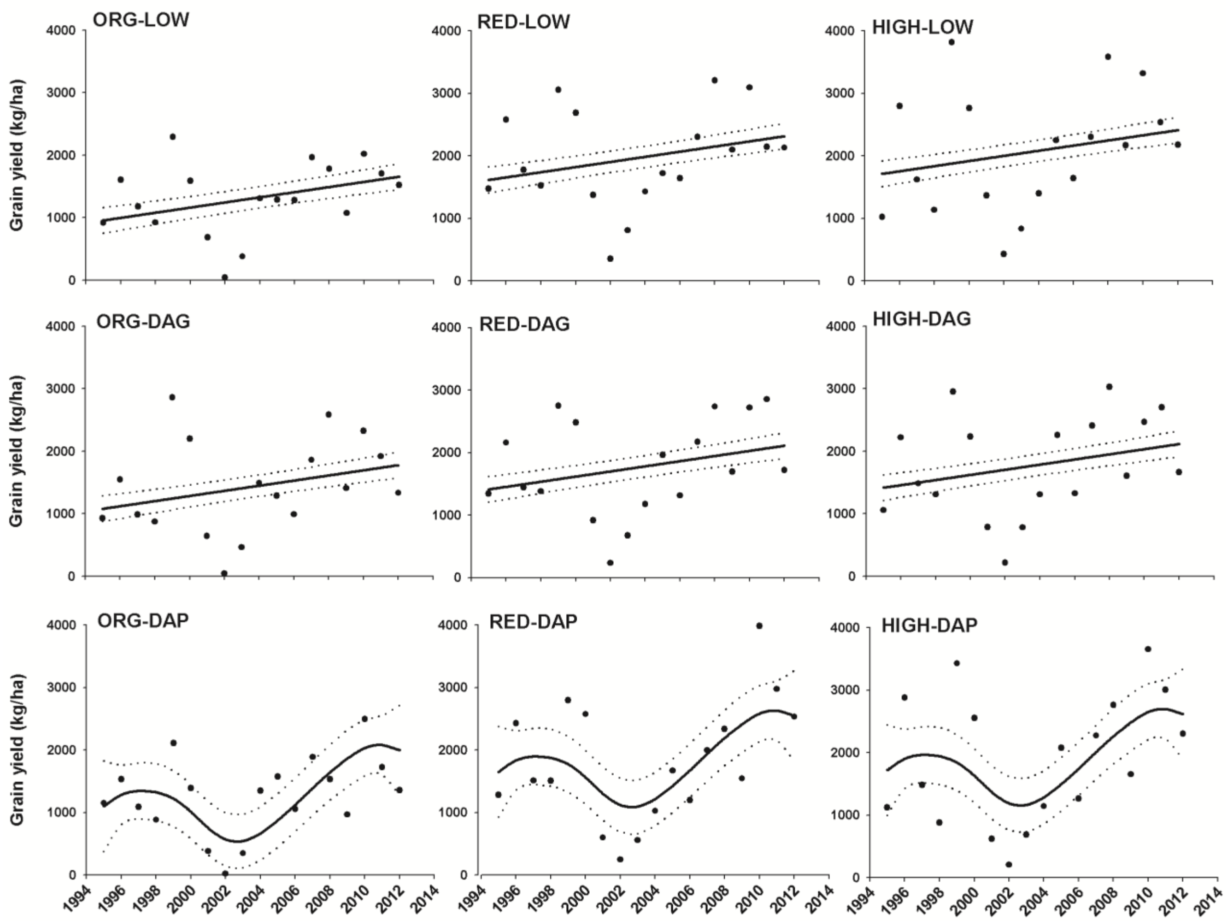

Figure 3.8. Eighteen-year trend in yield (excluding forage and manure phases) assessed in ACS at Scott. Black circles represent observed mean yield for each year. The solid line represents the linear/nonlinear prediction of weed biomass over time. Dotted lines represent the upper and lower 95% prediction interval.

3.5 Discussion

This study reveals that three cropping systems had differences in weed abundance and crop yields over time. Reducing agrochemicals (fertilizers and pesticides) and eliminating tillage did not negatively affect weed management or crop yields, as there were no differences between the RED and HIGH systems in weed abundance or crop yields. Therefore, these results confirmed that reducing synthetic inputs (fertilizer and herbicides) and eliminating tillage is possible without sacrificing yields or weed management in conventional crop production systems. Furthermore, considering the known environmental benefits of no-till systems (Grandy et al. 2006), the no-till reduced input systems may be more sustainable for the Canadian prairies than tillage-based, high input cropping systems.

As observed in this study, having a fallow period in crop rotations often improves weed control in many cropping systems (Hume 1982; Blackshaw 1994; Derksen et al. 1994). Therefore, considering the weed management and crop yield benefits found in this study, no-till systems with a crop-crop-fallow (LOW) rotation are the most effective for the Dark Brown soil zones. However, despite being less effective in weed management compared to the LOW diversity rotations, the diversified annual grains (DAG) rotations had comparable yields as the LOW rotations, and therefore could be the better choice for most farmers for economic reasons. Organic systems, characterized by complete elimination of external synthetic chemical inputs, resulted in greater weed abundance compared to the two conventional systems (HIGH and RED). This study found that the long-term organic crop production practices failed to reduce weed abundance in comparison to non-organic systems, which is in accordance with prior studies that found ineffective weed management to be the main problem in most organic systems (Ryan et al. 2009). Therefore, better weed management strategies are warranted in organic systems.

Increasing the crop diversity in all three input systems from fallow-grains to continuous diverse annual cropping or annual-perennial cropping have increased weed biomass in this study. Increasing crop diversity in rotations previously found to reduce weed abundance (Liebman and Dyke 1993) and is believed to be the key strategy for long-term weed management, particularly in organic systems. Generally, a rotation with crops of different life cycles and phenologies than the monoculture crop is disruptive to the weeds life-cycle. Accordingly, Entz et al. (1995)

concluded that for most Canadian farms, having a three-year alfalfa crop in the rotation will reduce weed abundance. Furthermore, Kegode et al. (1999) found low weed seed production when a perennial crop was included in the rotation. However, in the present study, we found that increasing the cropping diversity, with a three-year alfalfa forage crop, did not improve weed management but rather reduced crop productivity, compared to the other two rotations. Although earlier studies by Hoyt (1990) and Entz et al. (1995) identified greater yield benefits for crops followed by perennial crops, Bell et al. (2012) recently confirmed that alfalfa crop rotations have low carbon stocks and nutrients compared to annual cropping. Bell et al. (2012) also found that nutrients are more deprived in organic systems, particularly plant-available phosphorus. Hoyt (1990) found that most yield advantages of forages compared to continuous crops were after the first eight years post-termination, but these advantages decline later. The main reason for low productivity is that the biomass is removed for hay and not returned to the soil. Therefore, based on the results of this present study, increasing the diversity by simply including perennial forages can be counter-productive unless there are substantial gains in weed control.

Long-term trends (both linear and non-linear) in weed abundance and crop yields were identified in the ACS study using the random spline model approach. This is in contrast to other long-term crop rotation studies which failed to identify temporal trends (Barberi and Cascio 2001; Hiltbrunner et al. 2008; Lundkvist et al. 2008). Weed density in ORG systems was high and less variable over time compared to the weed densities in the RED and HIGH systems. Greater year-to-year fluctuations in weed density in the two conventional systems were due to good weed control years and some poor weed control years with herbicides. Consistently high weed density over time in ORG systems implies that weed control strategies are not effective in organic systems. This is probably due to the inability to use in-crop tillage (harrowing) in some crop phases due to their poor tolerance to mechanical damage. Less variability in weed biomass in the perennial rotations compared to the other two rotations could be due to less variability in crop phases in the perennial system compared to annual grains. Despite differences in overall weed abundance among cropping systems, all systems showed increasing trends (linear or curvi-linear) over time for weed density and weed biomass. Even with chemical weed control, none of the conventional systems showed a decline in weed abundance over time, indicating the persistent nature of weed problems in the current conventional cropping systems as well.

Similarly, an increase in weed abundance over time, irrespective of crop management, suggests that long-term changes in environmental conditions might have favored weed growth. An increase in rainfall observed over time could be one such reason for the long-term increase in weed abundance. Therefore, this study restates the importance of edaphic factors when understanding long-term weed dynamics and crop yields.

The low crop yields produced by the organic rotations in the ACS are in agreement with of many others (Entz et al. 2001; Ryan et al. 2004; Welsh et al. 2009; Seufert et al. 2012; Ponisio et al. 2015). However, several long-term studies in the USA found that soybean, maize, and oat yields were similar among organic and conventional systems (Porter et al. 2003; Sanchez et al. 2004; Pimentel et al. 2005; Smith et al. 2007). Importantly, most of the studies that found higher or similar yields among organic and conventional crops focused on organic systems in the USA, where purchased manure, compost, and food waste were used to supply nutrients (Liebhardt et al. 1989; Clark et al. 1999). In contrast, the current study used a minimal amount of compost (applied only after each six-year cycle to the annual-perennial [DAP] rotation). Therefore, soil productivity in the ACS systems could be low. Malhi et al. (2009) identified low soil P levels in the ACS organic cropping systems and others (Martin et al. 2007; Knight et al. 2010) have also found low soil P levels in organic cropping systems in western Canada. Even though increasing the crop diversity was found to be the main strategy used in most organic systems to maintain soil fertility and manage weeds, with time, grain-based annual cropping systems can become N limited, and rotations that include perennial forage can become P limited (Welsh et al. 2009). Therefore, relying on crop rotations is not sufficient for enhancing soil fertility levels in organic cropping systems.

The continuous increase in crop yields despite the concurrent increase in weed abundance suggests that weeds are not influencing crop yields. Since this study used residual weeds, they might have less competition on the crop since the crop is well established at that stage. However, the results from the chapter five showed that early weed abundance had minimal effect on reducing wheat yields in the ACS trial and that lower yields from the organic systems were due to lower crop productivity rather than weed competition. Significantly high weed abundance and lower crop productivity in organic versus conventional systems in this study and in others (Entz et al. 2001; Posner 2008; Seufert et al. 2012; Ponisio et al. 2015) support the common argument that organic systems cannot maintain crop yields for a long period of time. However, none of the previous studies examined yield trends in organic compared to conventional systems. In this study, we revealed that given good environmental conditions, organic yields increase over time despite a concurrent increase in weed abundance. However, overall lower crop yields in organic than conventional systems (35% less yield in organic) indicates that organic systems require alternative crop rotations to enhance the soil fertility to be competitive and attractive to farmers. The increase in crop yields over time in all the systems could be a result of the long-term changes in weather conditions that favor crop production, particularly the increase in rainfall.

Overall, this long-term cropping systems study revealed that cropping systems differentially affect weed abundance, but weeds may not be the main determinant factor affecting crop yields. Even though the increase in weed abundance not directly influenced crop yields, it can dictate the crop management practices in short and long-term as farmers tend to use weed abundance as the guideline for weed control decisions. Hence, sustainable weed control strategies are required for both conventional and organic systems to manage weed densities to acceptable levels.

3.6 Conclusions

The results from the analysis of the weed density, weed biomass and crop yields of the long-term ACS cropping systems study concluded that the no-till reduced input system is comparative in managing weeds and in crop yields with the tillage based high input system; hence, eliminating tillage and slightly reducing the amounts of inputs such as fertilizers and pesticides is possible without a yield penalty and without future aggravated weed abundance. Among conventional systems, the crop-crop-fallow rotation was found to be the most effective in terms of weed control, and in crop yields. However, continuous cropping with diverse annual crops had comparable yields even with greater weed abundance and could be the choice for most farmers due to the economic reasons. Increasing the crop diversity with the current crop rotation strategies used in this study was not sufficient to enhance the crop yields or decrease weed abundance over time in any of the input systems. Total elimination of fertilizers and pesticides in the form of organic management substantially increased weed abundance and reduced the crop yields compared to conventional systems. However, greater weed abundance throughout the time period did not cause a continuous decline in crop yields in organic systems. All cropping systems showed an increasing trend in weed abundance as well as crop yields over time. Beside crop management practices, short term changes in environmental factors, particularly rainfall found to influence year-to-year variation in weed abundance and the long-term increase in rainfall found to influence the long-term increase in weed abundance and crop yields in all cropping systems.

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Prologue (Chapter 4)

Differences in cropping systems not only impact weed abundance, but also can affect the weed community composition. The weed community in a given location at a given time is composed of the interacting individuals belonging to different species. The ecological constraints in terms of crop and weed management practices can provide diverse selection pressures on the weed community. Differences in species morphological, phenological and physiological mechanisms can enable them to respond to these diverse disturbances indifferently. Therefore, the continuous implementation of a cropping system can result in a unique weed community composition with species more adapted to those ecological disturbances created by that particular cropping system. Other than these human involved processes, random environmental perturbations are important in determining plant communities. It is important to identify the long-term weed community compositional changes in order to distinguish these crop managements based processes from random environmental conditions. Therefore, the fourth chapter will attempt to understand the differences in the weed community composition and the structure among the ACS cropping systems.

4.0 LONG-TERM IMPACTS OF ORGANIC AND CONVENTIONAL CROPPING SYSTEMS ON WEED COMMUNITY DYNAMICS: USE OF PRINCIPAL RESPONSE CURVE TECHNIQUE

4.1 Abstract

Weeds have acquired specific evolutionary adaptations to the diverse crop and weed management strategies in a cropping system. Organic and conventional cropping systems often use different crop management practices that can result in different weed community compositions. Therefore, changes in crop production practices such conventional to organic, and tillage based systems to no-till systems and differences in crop rotation diversities can result in difference in weed community composition that can have management implications. A study was carried out to understand the weed community dynamics in a long-term alternative cropping systems study (ACS) at Scott, Saskatchewan, Canada, which reflects, the past and the present cropping systems that most farmers practice in the prairies. Long-term (18 year) weed community composition data in a wheat crop of ORG (organic), RED (reduced input no-till) and HIGH (high input conventional tillage) input systems with three levels of crop rotation diversities; LOW (low diversity), DAG (diversified annual grains) and DAP (diversified annuals and perennials) were used to study the effect of contrasting cropping systems on residual weed community composition using the Principle Response Curve (PRC) technique. Year-to-year environment driven random changes were found to be the predominant factor causing fluctuations in the weed community composition more than the cropping systems. Organic systems clearly differed from the two conventional systems in most years and were more diverse in composition compared to the two conventional systems. The two conventional systems were similar in the weed composition in most years. The differences in weed composition among organic crop rotations were not profound, but in the two conventional systems, the diversified annual grain systems showed more diverse community throughout many years. Increasing the diversity of crop rotations with annuals and perennial crops did not changed the community composition. Therefore, this study concluded that moving from tillage-based high input conventional system to a no-till reduced input system did not cause significant changes to the

weed community but organic systems showed more diversity probably due to increase in some difficult to control species.

4.1 Introduction

Weeds have specific evolutionary adaptations to the diverse crop and weed management strategies in a cropping system, and thereby can sustain their populations under a wide range of crop and weed management conditions (Ghersa et al. 1994). Since weeds compete for resources with crop plants and cause substantial economic losses (Oerke 2006), controlling them is one of the main objectives in crop production. In the past, weed science had ignored studying weed communities, and instead focused on individual weed species and their responses to weed control practices. However, it is now known that a weed population occurs within a community; hence, an increase or decrease in abundance of one species creates opportunities for other species to increase or decrease in abundance (Booth and Swanton 2002). Therefore, in order to devise long-term sustainable weed management strategies, understanding crop management induced changes in weed community composition is important (Clements et al. 1994; Hobbs and Humphries 1995). Despite early debates, plant ecologists now believe that the plant community composition is a result of both deterministic and random processes in the environment (Chase 2007). Thus, in agroecosystems, weed species composition is assumed to follow the temporal pattern of the environment changes resulting from the interaction between climate variables and agronomic variables related to a particular farming system (Ghersa et al. 1994). Compared to plants in natural environments, weeds in agro-ecosystems undergo continuous predictable disturbances in the form of crop management practices (cropping systems); hence, deterministic processes can be more important in determining such communities (Chase and Liebold 2003).

Understanding weed community dynamics demands the integration of understanding of environmental factors, crop management practices and community level interactions. According to community assembly theory, plant communities are assembled and they follow trajectories (community states) through time controlled by both biotic and abiotic factors (Diamond 1975). Membership in the community is limited by filters or ecological constraints acting on the species pools (Belyea and Lancaster 1999). Accordingly, weed communities are believed to be assembled (Booth and Swanton 2002). Crop management practices can be highly diverse depending on the type and the amount of inputs being utilized, types and length of crop rotations, and weed control practices adopted. Therefore, the diversity in terms of crop management practices can create differences in environmental filters that select a particular type of species over the others (Booth and Swanton 2002).

Herbicides, crop rotation and tillage systems are the most important agronomic practices that influence aboveground and below-ground weed composition (Froud-Williams 1988; Léger and Samson 1999; Cardina et al. 2002). There have been few studies carried out on the overall impact of organic and conventional cropping systems on weed community dynamics (Hyvönen et al. 2003; Roschewitz et al. 2005; Ryan et al. 2010). Studying the overall cropping systems effect within a given region can provide better insights on the combined effects of contrasting crop management practices such as tillage, fertilizer, crop rotation and weed control strategies on weed community assembly. The few studies that have been conducted have found that the cumulative effects of organic and conventional systems have caused differences in species composition and the species diversity (Menalled 2001; Hyvönen et al. 2003; Ryan et al. 2010). Still, most of these long-term studies tend to look at point estimations or cumulative effects over a time period on the species composition rather than the actual plant community dynamics over time. Since random environmental perturbations often influence the annual weed community composition more than crop management (Thomas and Dale 1991; Dale et al. 1992; Andersson and Milberg 1998), estimating the weed composition at a particular time point may not be ideal to understand their dynamics. Hence, there is a need to look at annual variations as well as long-term trajectories in weed community composition among contrasting cropping systems in a given region.

Cropping practices in the Canadian prairies are dynamic as they change over time in order to enhance productivity and maintain sustainability. Due to the growing awareness of negative environmental impacts of tillage based high input crop–fallow cropping systems, alternative cropping systems such as no-till reduced-input systems or organic systems with more diverse crop rotations are widely practiced in the prairies (Dhuyvetter et al. 1996; Lafond et al. 1992, 1993; Zentner 2002). Even though the agronomic and environmental benefits of these alternative cropping systems have been evaluated, their impacts on long-term weed community dynamics are not known. Since weeds are believed to be the most yield limiting factor in most of the low input and organic systems and herbicides are the most used synthetic pesticides in conventional systems, a comprehensive understanding of the long-term impact of these two contrasting cropping systems on weed communities can help to devise sustainable weed management practices.

Advanced statistical approaches are needed in order to understand the impacts of cropping systems and their interactions with the environment on the weed community composition. Multivariate statistical tools are the most widely utilized analytical techniques for studying plant community composition. Even though multivariate techniques are being commonly utilized in ecology, these techniques are underutilized in weed science. Ordination techniques such as canonical discriminant analysis (CDA), canonical correspondence analysis (CCA) and redundancy analysis (RDA) are the most common multivariate constrained ordination techniques used to study the relationship between crop management and weed community composition (Derksen et al. 1993; Shrestha et al. 2002; Moonen and Barberri 2004; Sosnoskie et al. 2006; Fried et al. 2008; Ryan et al. 2010). However, these techniques only examined the cumulative effects over a given time period rather than temporal dynamics of the species composition; hence, these techniques are not sufficient to understand the crop management induced long-term temporal dynamics in plant communities. Furthermore, none of the above techniques consider the repeated nature of the data sampling in long-term experiments. To overcome these limitations in common ordination methods, the principal response curve method (a variant of RDA) has been utilized in ecotoxicology studies (Van den Brink and Ter Braak 1999) and in restoration ecology studies (Pakeman 2004; Vandvik et al. 2005; Palik and Kastendick 2010; Poulin et al. 2013). This technique can be useful in long-term weed community studies in cropping systems when repeated weed abundance data collected in the same experiment to understand weed community dynamics. Therefore, the aim of this study is to use the principal response curve (PRC) method to understand weed community dynamics in a long-term alternative cropping systems study (ACS) at Scott, Saskatchewan, Canada. The ACS experiment was established to study the agronomic, economic and environmental aspects of cropping systems in the Canadian prairies (Brandt et al. 2010). This study includes three levels of input systems (high, reduced and organic) and three levels of crop rotation diversities (low diversity, diversified annual grains and diversified annuals and perennials). Overall, this study hypothesized that the diverse cropping systems can act as contrasting ecological filters where weed community composition progressively differ among cropping systems over a long time period. Secondly, it is hypothesized that the diversity of the weed community is high in more diverse crop rotations and in organic systems due to more diverse ecological filters.

4.3 Materials and Methods

4.3.1 Location and the experimental design

An alternative cropping systems trial was established in 1994 at Scott, Saskatchewan (52^{o}22'; 108^{o}50', elevation=713 meters) in order to evaluate the long-term impact of diverse cropping systems in the Canadian prairies. It is located near the geographic center of the Canadian prairies in the Dark Brown soil zone. The details of the experiment were explained in Brandt et al. (2010). The experiment is a four replicate split-split plot with main plot treatments having three levels of inputs and sub-plots with three levels of crop rotation diversity. Each crop rotation had six crop phases carried out for six years. The year 1994 was the benchmark year where a barley crop was seeded on to the experimental site. All the treatments were applied from the year 1995 and carried out for 18 years. The two main treatments were the input level (systems) and the crop diversity level (rotations) with three levels under each treatment. Among input levels, organic (ORG) system used tillage and non-chemical pest control and soil nutrient management strategies. The reduced system (RED) was a no-tillage system utilizing site specific integrated management of pests and nutrients (Brandt et al. 2010). The high input system (HIGH) was a tillage based system which used pesticides and fertilizers based on requirement according to conventional recommendations.

Three levels of crop diversities were used in a six-year crop rotation cycle, including low diversity (LOW), diversified annual grains (DAG) and diversified annual perennials (DAP). Crop rotations differed between systems to reflect commonly grown crops and practices for each particular system. All the crop phases in all cropping systems are given in the Table 4.1. In this study, only the wheat phase that was commonly represented in all cropping systems was used for the analysis. The details of the crop phases and their management were described in chapter three.

Table 4.1. Crop phases of all cropping systems in the Alternative Cropping Systems trial near Scott, SK.

Input	Rotation	Crop phases
HIGH	LOW	Fallow-**Wheat**-Wheat-Fallow-Canola-Wheat
	DAG	Canola-Wheat-Pea-Barley-Flax-**Wheat**
	DAP	Canola-**Wheat**-Barley-Alfalfa-Alfalfa-Alfalfa
RED	LOW	GM-**Wheat**-Wheat-Fallow-Canola-Wheat
	DAG	Canola-Wheat-Pea-Barley-Flax-**Wheat**
	DAP	Canola-**Wheat**-Barley-Alfalfa-Alfalfa-Alfalfa
ORG	LOW	GM-**Wheat**-Wheat-GM-Mustard-Wheat
	DAG	GM-**Wheat**-Pea-Barley-GM-Mustard
	DAP	Mustard-**Wheat**-Barley-Alfalfa-Alfalfa-Alfalfa

*Weed data only from crop phases highlighted were used for the weed community analysis

4.3.5 Data collection

Residual weed counts (after application of weed control methods) were taken by using twenty 0.25m^2 quadrats in every year from 1994-2012. Ten quadrats were randomly placed along the North-East to South-West directions and another 10 quadrats were placed randomly along North-West to South-East directions of each plot which is about 40 m x 12.5 m in size. Weeds were identified to their species level.

4.3.6 Data analysis

For this study, the data collected from a selected wheat phase in each cropping system were used. The wheat phase was selected as it was the most common phase that represents the main grain crop phase in all the rotations. All the weed species data collected were used for the multivariate and univariate statistical analysis. The multivariate statistical analysis technique, constrained ordination was used to reduce the dimensionality of the species data constrained by the treatment variables and the experimental design. The treatment variables were the nine combinations of the three input systems and the three crop rotation levels and their interactions with time. The block and split plots were considered as covariables which represents the spatial scales of the treatment applied. The three input systems were the main plots and the three rotations were the split plots. Several runs of multivariate analysis using log transformed data were carried out using Canoco for Windows 4.5 (Ter Braak and Smilauer1998). Initially, de-trended correspondence analysis (DCA) was carried out for the species data in order to identify the gradient length (Ter Braak and Prentice 1988; Leps and Smilauer 2003). A longer gradient length (>4.0) indicates a unimodal distribution of data (Ter Braak and Smilauer 2002) hindering the adoption of linear methods in ordination analysis, such as principal component analysis (PCA) and redundancy analysis (RDA). For this data set, redundancy analysis (RA) was carried out as it is a constrained ordination technique and also that the gradient length was < 4.0. In order to quantify the amount of variation in the species community composition explained by each component (treatments, time, spatial variation) and their statistical significance, several runs of RDA was carried out using several permutation tests to test for the effect of time, input x rotation, input x time, rotation x time, input x rotation x time and spatial variability (block and split plots) on the species composition. In each permutation test, the individual components were set either as environmental variables (treatments) or as covariables. The spatial variation identified as replication (blocks) and spatial pattern of sampling plots (split plot design) was used as co-variables for all tests. A Monte Carlo test with 999 permutations was used to test the significance of each component on the species composition and declared significant at $P < 0.05$.

The principal response curve method was utilized to study the changes in species composition over time. Principal response curve method is a variant of the RDA for repeated observation designs (Van den Brink and Ter Braak 1999). This method allows one to contrast the treatments to a specified control (treatment time series or a time point in the experiment) and determine changes over time period. Principal response curves were derived from the RDA output where treatments by time (input x rotation x time) were set as constrained variables and spatial pattern as covariables. The pre-treatment year 1994 was set as the reference time point for the principal response curves where species community changes influenced by treatments and their interaction with time is expressed relative to the species composition in each treatment in the year 1994 in the ordination diagrams. To obtain principal response curves, standardized canonical regression coefficients (Cdt), standard deviations of environmental variables (Sd) and total standard deviation in the species data (TAU) were obtained from the RDA output (Van den Brink and Ter Braak 1999). Principal response curve scores (canonical coefficients) were obtained using the following equation according to (Van den Brink and Ter Braak 1999):

$$(TAU \times C_{dt})/Sd \qquad [4.1]$$

After obtaining the PRC scores they were graphed against time for each treatment. Species weights (b_k) for the first axis were obtained from the RDA and was tabled in a separate table with the ordination diagram. The species weights were obtained using the following equation according to (Van den Brink and Ter Braak 1999):

$$\exp (b_k \times C_{dt}) \qquad [4.2]$$

The equation (4.2) expresses the proportional change of species$_{(k)}$ in treatment$_{(d)}$ and in year$_{(t)}$ relative to the species abundance in the year set as the reference or the control time point (in this study it is the year 1994). The significance of the first ordination axis (effect of treatments and their interactions with time on species composition represented by the first canonical axis) was tested using the Monte Carlo test with 499 permutations and declared significant at $P < 0.05$. To test the significance of the second canonical axis, an additional RDA was carried out using sample scores of the first axis as a covariable (constrained) and treatments and their interactions with time used as environmental variables as in the initial RDA.

In order to determine the species associated with particular cropping system (cumulative effect over 18 years) indicator species analysis was carried out using IndVal index (Dufrêne and Legendre 1997) using the package “indicspecies” (De Caceres and Legendre 2009) in R software version 3.1.2 (R core team 2015). Species with significant association ($P < 0.05$) were determined to be associated with the particular group of cropping systems. Only the species with an indicator value > 0.2 were shown in the results. The overall species community structure was determined by calculating the species diversity indices such as species richness, evenness and

Shannon Weiner diversity index for each plot using the package BiodiversityR (Kindt and Coe 2005) in R software version 3.1.2 (R core team 2015). All these biodiversity indices for each treatment in each year were then analyzed using repeated measures ANOVA using the MIXED procedure in SAS software version 9.3 (SAS INS 2011) to compare the mean species diversity indices among cropping systems.

4.4 Results

4.4.1 Factors determining the weed species composition

Changes in weed community composition were influenced by both the environmental factors (time) and crop management factors (Table 4.2). The time x input x rotation interaction accounted for the greatest amount of total variation at 56%. This indicates that there were temporal changes in species composition that are specific to each cropping system (Table 4.2). Time had an overall effect on weed composition and accounted for 24% of the variation. Most of the temporal effects on weed community composition could be explained by the changes in rainfall pattern and temperature throughout the period. The total and monthly rainfall during the growing season (Figure 4.1A) and the monthly temperature (Figure 4.1B) showed greater year to year fluctuations. Crop input and rotation interaction explained 20% of the variation in weed species composition that was not explained by temporal and spatial variability. The interaction of time by input systems accounted for 12% of the variation and the time by rotation accounted for 10% variation in the species community composition. The spatial variation alone accounted for 4% of the total variation, but was not statistically significant.

4.4.2 Changes in species composition over time

The principal response curves were used to understand the species community composition change over the time period. Of the 56% of the variation explained by input x rotation x time interaction (Table 4.2), 39 % was explained by the first canonical axis and 13% explained by the second canonical axis of the PRC (Table 4.2).

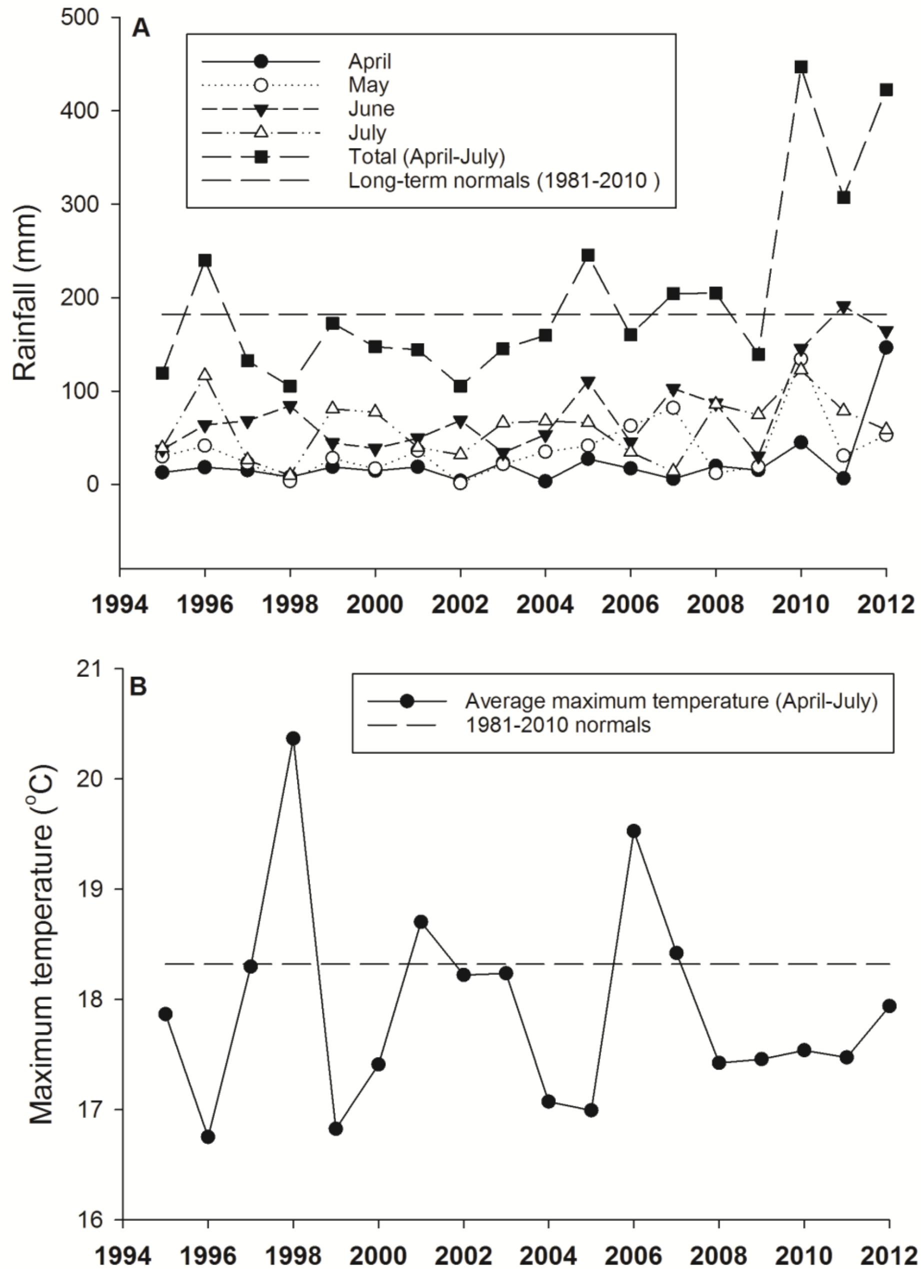
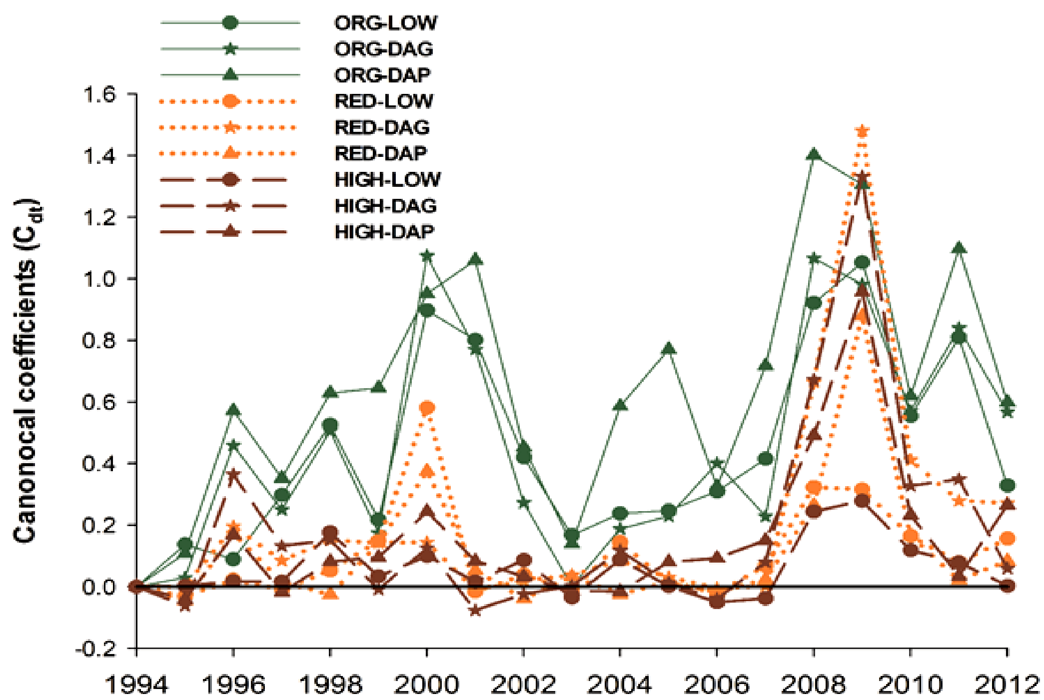


Figure 4.1. Yearly total and monthly growing season rainfall (A) and growing season average maximum temperature (B) at the ACS site in Scott, Saskatchewan, Canada. The dotted lines represent the long-term normals and the solid lines represent the mean growing season (April-July) total rainfall and maximum temperature.

Table 4.2. The amount of variation of the species composition extracted by the first two ordination axes attributed to cropping systems, time and the spatial variation.

Treatments	Covariables	Total	First axis	Second axis	*P* value
Time x Input x Rotation	Spatial	56%	39%	13%	0.002
Time	Input x Rotation, Spatial	24%	63%	13%	0.002
Input x Rotation	Time Spatial	20%	79%	9%	0.002
Time x Input	Time, Rotation x time, Spatial	12%	40%	20%	0.002
Time x Rotation	Time, Input x Time, Spatial	10%	33%	19%	0.002
Spatial	Time, Input x rotation x Time	4%	36%	19%	0.5

* Weed species data collected in the wheat phases from all cropping systems in the ACS trial during 1995-2012 were used in the ordination.



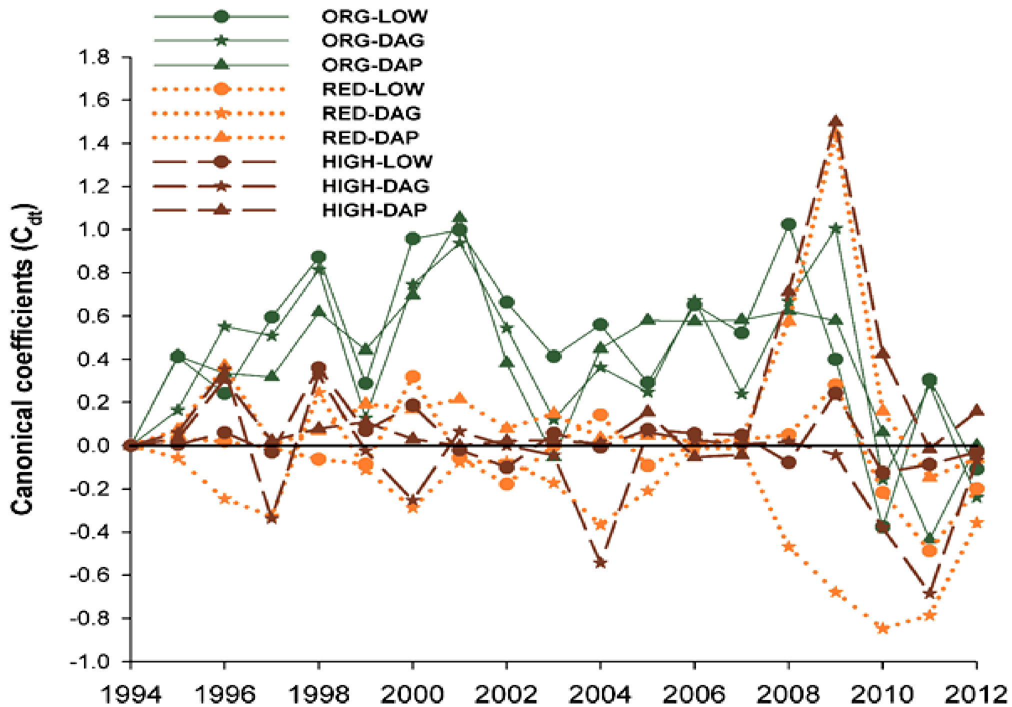
Latin name	Species weight (b_k)
C. album	2.69
S. viridis	1.56
C. bursa-pastoris	1.23
P. convolvulus	0.96
C. tectorum	0.81
A. fatua	0.71
L. usitatissimum	0.68
T. arvense	0.66
B. napus	0.63
A. retroflexus	0.45
T. officinale	0.44
A. albus	0.30
D. sophia	0.29
L. culinaris	0.27
P. aviculare	0.22

Figure 4.2. The first ordination axis (principal response curves) for the species abundance data collected in the ACS study from 1994-2012. The horizontal solid line at zero represents the reference time point (year 1994) and all the changes in the weed composition were explained by PRC curves for each treatment relative to the year 1994. From the 56 % of the variation in the weed community explained by input x rotation x time interaction, 39 % was explained by the first axis and was significant at *P* < 0.01. The table to the right of the graph provides the species weights (b_k), which indicates the association of the particular species to the principal response curves. The higher the value of the species weight for a particular species the greater the species follow the pattern in the PRC.

The first PRC axis explained 39% of the variability indicating significant changes in the species composition attributed to treatments over time compared to the year 1994 (Figure 4.2). The principal response curve above or below zero for any time point indicated changes in species composition relative to the year 1994. Species weights given in the table provided the association of the particular species to the principal response curve. The higher the species weight, the greater the particular species follow the pattern of the principal response curve particular to a treatment. For instance, in the year 1996 in ORG-DAP, the canonical coefficient was 0.58 (Figure 4.2); hence, the abundance of common lambsquarters (*Chenopodium album* L.) was exp (2.69 x 0.58) which means the abundance of common lambsquarters in the treatment ORG-DAP in 1996 was 4.7 times greater than the year 1994.

The first principal response axis was mostly found to explain the variation among input systems since they have shown to deviate apart along the first axis. Accordingly, the species composition in the three organic treatments began to change after the year 1994 which was the pre-treatment year. Importantly, the community composition was different in all years following 1994. However, apart from year to year variation there were no continuous trajectories in species community in any of the treatments over the time. Still, despite year-to-year variations, the weed composition in the organic systems was found to deviate clearly from the RED and HIGH systems in most years. Only in 2009, some of the rotation treatments within the RED and HIGH systems had a similar species composition to that of organic systems. Both RED and HIGH systems had similar compositional dynamics over time apart from a few years. In addition, the two conventional input systems (RED and HIGH) did not show clear departure from 1994 in terms of species composition in most years.

The species common lambsquarters, green foxtail *(Setaria viridis* L.*)*, shepherd's-purse (*Capsella bursa-pastoris* L.) and buckwheat (*Polygonum convolvulus* L.) were the most common species that tend to follow the pattern of the first PRC in all systems, but their relative abundance changed depending on the system and the year (Figure 4.2). The common pattern observed in community changes was distorted in the years after 2008. After 2008 the two conventional systems showed greater changes in the weed community and clearly showed differences among rotations as well.



Latin name	Species weight (b_k)
C. album	1.19
B. napus	0.64
T. arvense	0.28
M. sativa	0.05
H. vulgare	0.03
A. retroflexsus	-0.08
C. bursa-pastoris	-0.25
P. convolvulus	-0.25
T. officinale	-0.42
L. usitatissimum	-0.57
C. tectorum	-0.67
S. viridis	-0.81
A. fatua	-1.15

Figure 4.3. The second axis (second set of principal response curves) for the species abundance data collected in the ACS study from 1994-2012. The year 1994 was used as the reference time point and all changes in the weed composition explained by PRC for each treatment relative to the year 1994. Of the 34% residual variation (variation left after excluding the variation explained by the first axis), 13% was explained by treatment*time interaction and it is significant at *P* < 0.01. The table to the right of the graph provides the species weights (b_k), which indicates the association of the particular species to the principal response curve. The higher the value of the species weight for a particular species the greater the species follow the pattern in the PRC.

The second principal response axis explained 13% of the treatment x time interactions that were not explained by the first principal response axis (Figure 4.3). In general, crop rotations were found to separate along the second axis more than in the first axis. The weed species common lambsquarters, volunteer canola (*Brassica napus* L.), and stink weed (*Thalapse arvense* L.) were highly associated with treatments with a PRC curve above zero while weed species wild oat, green foxtail and narrow leaved hawksbeard *(Crepis tectorum* L.) were declining in abundance (Figure 4.3). Until 2008, the three organic rotations were found to follow a distinct pattern compared to the HIGH and RED rotations except for some few years. After the year 2008, abrupt changes in species composition can be observed probably due to greater fluctuation in total rainfall (Figure 4.1) and this is similar to the response found on the first axis (Figure 4.2). Among conventional systems, crop rotations were found to diverge over time in terms of species composition. The diversified annual rotations (DAG) in both the HIGH and RED systems showed a distinct pattern compared to other treatments. In most years, these two treatments showed negative coefficient values. Therefore, in these two systems, wild oat, green foxtail, narrow leaved hawksbeard and flax (*L. usitatissimum* L.) were the most abundant (Figure 4.3). Furthermore, the species common lambsquarters, volunteer canola and stink weed were declining in abundance in most years in these rotations. Wild oat was fairly low in abundance in most years in the annual-perennial rotations in all input systems revealing the effectiveness of a perennial forage crop in controlling wild oat. Another distinct pattern was observed in the diversified annual perennial rotation in RED and HIGH systems where increase in lambsquarters canola and stink weed, while decrease in wild oat green, foxtail and narrow-leaved hawksbeard species were observed. The HIGH-LOW and the RED-LOW systems were found to follow a similar pattern with less deviation from the year 1994. After the year 2008, the deviation in species composition was higher than the other years.

4.4.3 Overall species associations with cropping systems

Indicator species analysis showed distinct associations of weed species with some cropping systems, while some weeds were associated with more than one cropping system (Table 4.3). Weed species such as yellow mustard (*sinapsis alba* L.), common pepperweed (*Lepidium densiflurum* L.), Stork's-bill (*Erodium cicutarium* L.) and wild mustard (*Sinapsis arvensis* L.) were highly associated with organic systems with perennials in rotation (ORG-DAP) system indicating that they had more specialized niche requirements. The species brome grass (*Bromus inermis* Leyss) was mainly associated with reduced systems with perennials in rotation (RED-DAP) as it was planted in all DAP rotations during the first six years. Even though above species were particularly associated with few cropping systems, their mean abundance was fairly low. All the other most abundant species were found to be associated with more than one particular cropping system. One of the most abundant weeds, common lambsquarters was associated with all organic rotations as well as with the HIGH-DAG and HIGH-DAP rotations indicating some association with tillage systems. Green foxtail was associated with all organic systems and HIGH-DAG, HIGH-DAP and RED-DAG systems. Volunteer flax was common in DAG rotation in RED and HIGH as those were the rotations that used flax as a crop in the rotation. Volunteer canola was more specific to DAP rotations in both HIGH and RED systems.

4.4.4 Species diversity

Species richness (number of species per unit area) and species evenness was determined by the input by rotation interaction (Appendix C). Species richness was found to be the lowest in HIGH-LOW system (Figure 4.4A). Both DAG and DAP rotation in HIGH systems had a greater species richness. Similarly, within organic system, DAP rotation had the highest species richness. There were no differences in species richness among RED rotations. Organic DAP system found to have low evenness in species abundance (Figure 4.4B), indicating few species dominating. Among RED rotations, evenness was lower in DAG than other rotations. In HIGH input systems, the LOW diversity rotation had fairly high evenness than DAG and DAP rotations. Overall, Shannon Weiner diversity index indicated that ORG systems to be the most diverse and different from RED and HIGH (Figure 4.4C). Both HIGH and RED systems had similar diversity.

Table 4.3. Indicator values and their significance $p < 0.05$ for the species associated with the nine cropping systems at ACS in Scott.

	Organic			Reduced			High		
Species name	LOW	DAG	DAP	LOW	DAG	DAP	LOW	DAG	DAP
Chenopodium album	0.87***	0.87***	0.87***					0.87***	0.87***
Setaria viridis	0.85***	0.85***	0.85***		0.85***		0.85***	0.85***	
Thlaspi arvense	0.82***	0.82***	0.82***						
Avena fatua	0.74***	0.74***	0.74***	0.74***	0.74***	0.74***		0.74***	
Linum usitatissimum					0.7***			0.7***	
Brassica napus						0.64***			0.64***
Amaranthus retroflexus	0.64***	0.64***	0.64***		0.64***		0.64***	0.64***	
Medicago sativa			0.6***			0.6***			0.6***
Crepis tectorum		0.6***	0.6***	0.6***	0.6***	0.6***			
Capsella bursa-pastoralis	0.6**	0.6**	0.6**	0.6**	0.6**	0.6**		0.6**	0.6**
Taraxacum officinale	0.58*	0.58*	0.58*	0.58*	0.58*	0.58*		0.58*	0.58*
Amaranthus blitoides	0.53***	0.53***	0.53***				0.53***	0.53***	0.53***
Lens culinaris	0.5***	0.5***							
Polygonum aviculare	0.5***	0.5***	0.5***				0.5***	0.5***	
Amaranthus albus	0.49***	0.49***	0.49***	0.49***	0.49***		0.49***	0.49***	0.49***
Sinapsis alba			0.488***						
Lepidium densiflorum			0.424***						
Salsola kali			0.4***	0.4***	0.4***	0.4***		0.4***	
Portulaca oleracea	0.36*	0.36*						0.36*	
Hordeum vulgare			0.32*		0.32*		0.32*	0.32*	0.32*
Descurainia sophia		0.33**	0.33**	0.33**	0.33**	0.33**			
Cirsium arevense	0.31**	0.31**	0.31**	0.31**	0.31**			0.31**	
Erodium cicutarium			0.281***						
Sinapsis arvensis			0.279***						
Bromus inermis						0.226**			

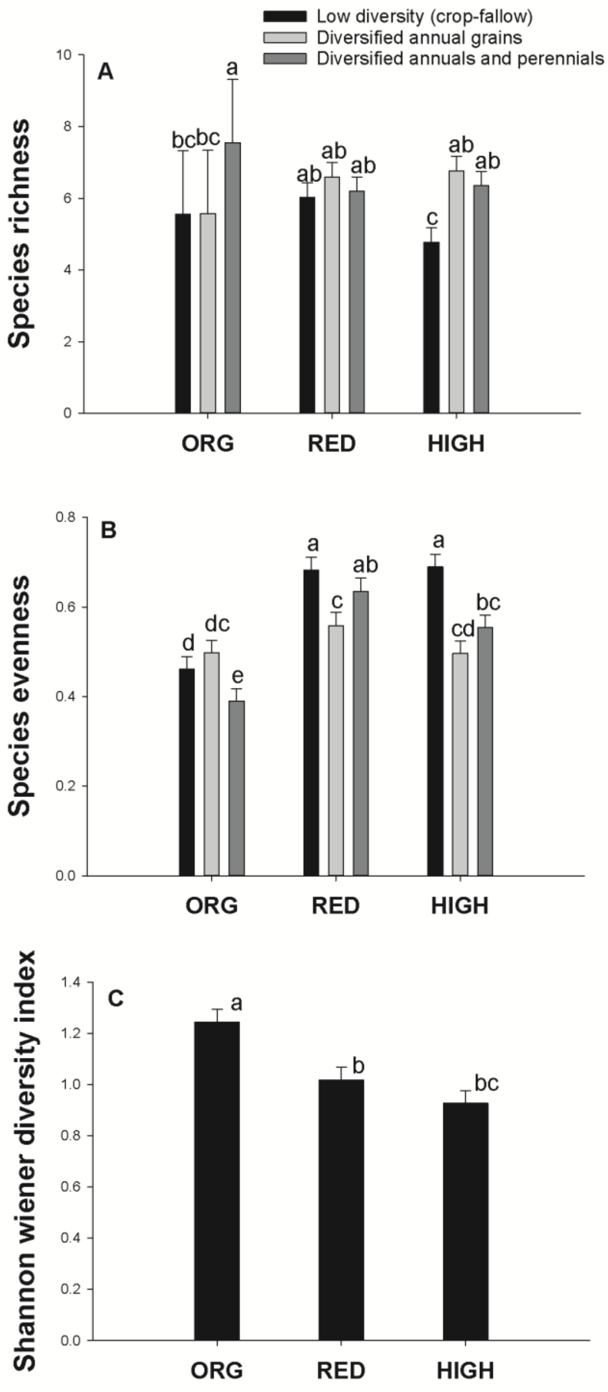


Figure 4.4. Mean species richness (A), species evenness (B) and Shannon Weiner diversity index (C) for cropping systems at ACS from 1995-2012. Error bars indicate standard errors of the lsmeans. Comparisons made between treatments with different letters indicate a significant different at LSD $P < 0.05$.

4.5 Discussion

Weed communities in a cropping system are generally being subjected to change over time due to the climatic conditions and due the crop management practices. The results of this long-term cropping systems study revealed that time dependent random variation in the environmental conditions could be the most important single factor that determines the weed community composition. However, some of the random variation that is not accounted for crop rotation and the input systems in this study may be also due to the differences in crop entry points which was not captured in this analysis as this study use a wheat phase that is not uniform in their entry levels in the rotations among treatments. The use of PRC method enabled the quantification of these random variations in the weed community compared to the traditional ordination techniques used in other studies. Similarly, some other studies revealed the importance of environmental factors on weed composition as well (Thomas and Dale 1991, Dale et al. 1992, Andersson and Milberg 1998). Crop production practices were the second most influential factor that affects species composition. Overall, the interaction of cropping systems and temporal changes were found to influence the weed community composition substantially. Importantly, none of the cropping systems showed a distinct weed community composition throughout the time period and none of the systems showed any trajectories (continuous changes). Therefore, we confirmed the importance of understanding real temporal dynamics of weed composition associated with cropping systems before making conclusions about the association of community with particular cropping systems or with particular management practices.

The organic systems had the most influence on changes in species community over time compare to the year 1994, indicating that organic systems have imposed contrasting ecological filters on weed community. Despite some minor changes in the abundance over time, organic systems had fairly distinct weed composition throughout the time for most years, indicating that these ecological filters are cumulative and persistent compared to the other systems. Consistently different weed composition indicates that weed communities in organic systems are either stable under the changes in ecological conditions or that the community is dominated by few species that cannot be controlled in organic systems. Summer annuals and winter annuals were the dominant weed species found in the organic systems, but these species were also high in abundance in the other input systems as well. Therefore, we did not observe a specific weed community in organic compared to the other two input systems. A greater abundance of weeds in organic systems due to lack of weed control strategies was identified in the ACS study (Chapter 5); hence, an increase in abundance of some weed species can cause distinct weed community in organic systems throughout the time period with a resistance to change. The differences in the use of inputs and inadequate weed control could have caused organic systems to be distinct in weed community response over time. Differences in types and the intensity of fertilizer application can influence the weed composition to a greater degree (O Donovan et al. 2007; Smith et al. 2010). Organic systems in the ACS have a low fertility status (Chapter 5), but can have diversity in resource dynamics (Smith et al. 2010; Ryan et al. 2009) and thus differentially influence weed emergence. Weed species such as common lambsquarters, green foxtail, stink weed and wild buckwheat were the dominant species in organic systems. Among these common lambsquarters and green foxtail species were found to be the most dominant two species in ORG systems indicating the inability to control weeds in organic systems. The less selective disturbances in mechanical weed control methods used in organic compared to the herbicides used in conventional system may be the most important factor for the differences in species community. Organic rotations not only had high overall abundance, but had more diversity in the species composition. Similarly, some other studies found high species diversity in organic compared to conventional systems (Menalled 2001; Ryan et al. 2010).

The effect of crop rotations on weed community composition was found to depend on the input systems. In organic systems, the differences in composition among crop rotations were not profound, but in the two conventional systems, the diversified annual grain rotation showed a more diverse community throughout many years. Even though the annual perennial rotations were functionally more diverse, the annual grain rotations which had many different annual crop species had a more distinct weed community composition. Smith et al. (2007) also found that the individual type of crop has more effect than the overall diversity in the crop rotation on weed composition. Still, the crop rotations with perennials had the greatest number of weed species. High species richness in these rotations could be either due to the greater functional diversity among crops grown or due to fewer disturbances because of the three-year perennial forage crop. Nevertheless, more than 60 % of the weed population comprised of three species in ORG-DAP indicating more dominance in few species.

Despite profound differences in the use of tillage among cropping systems, the two conventional systems (RED and HIGH) showed less differences in terms of species composition. In most previous studies, tillage was found to be the most influential factor determining the weed composition (Buhler 1995: Légère et al. 2005). If tillage is the predominant filter for weed communities, we should have observed a more different community composition in the reduced input system (RED) as it is the only system that tillage is not utilized. Hence, this study confirms that weed compositional dynamics are determined by many collective factors in the cropping systems than tillage alone. Blackshaw et al. (2005) also identified that even though tillage was usually associated with different weed compositions, weed species were not consistent with their response to tillage. Furthermore, there was not any increase in perennial species with no-till systems as observed in many other studies (Cardina et al. 1991; Moyer et al. 1994; Swanton et al.1993; Zanin et al. 1997). Since weed abundance data measured in this study is after applying weed control treatments, the in-crop weed control strategies should have been the strongest selective forces that determine weed community compared to the tillage regime. Accordingly, drastic increase in weed abundance and the composition in all systems found in the years 2000 and 2009 could be due to the failure of weed control strategies. Rainfall events might have interfered with both herbicide applications in conventional systems and mechanical weed control in organic systems, or these years had rainfall events after weed control triggering emergence of new weeds.

Common lambsquarters was found to be the most problematic in most of these cropping systems. Its wide occurrence in most cropping systems indicates its ability to survive under a wide range of cropping conditions. Interestingly, common lambsquarters was highly associated with tillage systems (HIGH and ORG) as it was not prominent in the no-tillage (RED) system. The fallow periods in the HIGH systems appears to be able to control this species as it was not associated with HIGH-LOW rotation as well. The grass species wild oat and green foxtail tended to increase while broadleaved species tend to decrease in abundance in the DAG rotation in both HIGH and RED systems. Inefficient selective grass weed control using herbicides in the wheat crop compared to broadleaf weed control could be the reason for the high number of grass species. Furthermore, in the DAG rotation, the wheat crop used in this study is followed by the less competitive flax crop which might have increased the abundance of these two weed species. Having a fallow period in the LOW diversity rotation or having a perennial forage crop in DAP rotations might have been able to suppress these weeds better than other rotations. The PRC showed consistent low abundance of wild oat in all the DAP rotations in most years. Similarly, Harker et al. (2016) found that wild oat was well controlled following a three-year alfalfa crop. Perennial forages help to reduce wild oat seed shatter due to early harvest of the crop for forage reducing its density over the longer period. Canola was grown in all conventional rotations, but the canola was found to be a problematic volunteer crop in HIGH-DAP and RED-DAP systems. Less soil disturbance in DAP rotations could be one of the main reasons for such observations. Similarly, in some other studies, volunteer crops were found in reduced tillage systems (Fraud Williams 1988; Derksen 1993).

By using the PRC method, this study allowed to understand the long-term temporal dynamics of species composition. Importantly, it allows us to compare the nine cropping systems simultaneously in terms of their temporal dynamics. In addition, it allowed us to monitor the changes in most important species or group of species over time for each cropping system. In this study, we used the benchmark year as the reference time point and all the changes in the species community were assessed with reference to the reference time point. This allows us to clearly understand the progress of the weed community development from the initiation of the cropping systems. Unless we understand the long-term dynamics of species composition it will not be meaningful to devise weed management strategies to manage weed species associated with cropping practices. This study revealed that even with current cropping systems diversity, some weed species are difficult to manage and are more adapted to diverse crop management conditions.

4.6 Conclusions

The use of principal response curve technique allowed us to determine the long-term temporal dynamics in weed community composition in relation to nine cropping systems in the Canadian prairies. Year to year environment driven random changes was found to be the predominant factor causing fluctuations in community composition than the cropping systems. Besides year-to-year variations, cropping systems were found to differ in weed composition throughout most years, indicating the impact of crop management on weed community assembly. The organic systems clearly differed from the two conventional (reduced and high input) systems, but the two conventional systems were found to be fairly similar in weed communities.

Among input systems, the differences in species composition were mainly due to the changes in relative abundance of species among cropping systems rather than contrasting differences in the types of species. The differences in weed composition among organic crop rotations were not profound, but in the two conventional systems, the diversified annual grain systems showed more diverse community throughout many years. Increasing the diversity of crop rotations with annuals and perennial crops did not cause any contrasting changes in the community composition. Overall, this study found that eliminating tillage and reducing inputs in conventional systems did not change weed community composition based on the wheat phase of the rotation, but moving to an organic cropping system can cause changes in the community composition due to increase in some difficult to control species.

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Prologue (chapter 5)

The previous two chapters identified the long-term influence of organic and conventional cropping systems on weed abundance and weed composition in the prairies. However, the impacts of these differences in weed dynamics on crop yields are not known. In addition, chapter three identified that the crop yields were lower in organic compared to the two conventional systems. Still, it is not known whether these low yields in organic systems were due to weed competition or due to other soil fertility related factors. Furthermore, some studies have found that crop-weed competition can be differ among cropping systems. Particularly, organic systems with diverse inputs and with diversity in crop rotations can have diversity in soil resources, thereby can cause more niche separation leading into less yield loss due to weed competition (Smith et al. 2010). Therefore, the work described in the chapter five was carried out to study the crop-weed competition between ORG and RED input systems in the ACS study. The objectives of the study was to find out the impact of weeds on crop yields and to find out the differences in yield loss due to crop-weed competition among the diverse cropping systems in the ACS study. A micro-plot field study was carried out with an additional four weed competition treatments within the ACS trial in all the three crop rotations within ORG and RED systems. In this chapter, for convenience, the RED input system was re-named as no-till conventional (CONV) and the three crop rotations were re-named as LOW, MEDIUM and HIGH for Low, diversified annual grains and diversified annual perennial rotations respectively.

5.0 DOES CROP YIELD LOSS DUE TO WEED COMPETITION DIFFER BETWEEN ORGANIC AND CONVENTIONAL CROPPING SYSTEMS?

5.1 Abstract

High weed abundance in organic crops, is thought to be a key factor contributing to the greater yield loss in organic compared to conventional cropping systems. However, even with greater weed densities than conventional systems, some organic systems have yields comparable to conventional systems, suggesting that cropping systems might differ in yield loss due to weed competition. The diversity in soil nutrient resources due to diversity in crop rotations and variable inputs might enhance crop tolerance to weed competition. We assessed the long-term effects of contrasting levels of crop rotations (low, medium and high diversity) on weed density, weed biomass and wheat yield loss in organic and no-till conventional cropping systems using a micro-plot study within a long-term cropping systems trial at Scott, Saskatchewan, Canada. Weed density and biomass were found to be 4X higher in the organic systems than in the conventional systems. Under standard weed management practices, organic had 44% lower yield than the conventional. Lower yields in organic even without weed competition suggest that the lower yields are due to low soil productivity rather than weed competition. No differences in yield loss were observed among the organic and conventional systems or among the diverse crop rotations. We conclude that the organic management practices and/or increased crop rotation diversity did not enhance yield or reduce yield loss to weed competition due to the factors associated with lower soil fertility.

[1]Chapter 5 of this dissertation has been accepted (with minor changes for formatting) in the Weed Research Journal as: D Benaragama, S J Shirtliffe, E N Johnson, H S N Duddu & L Syrovy (2016). Does crop yield loss due to weed competition differ between organic and conventional cropping systems? I designed and implemented the experiment, collected and analyzed samples, as well as conducted statistical analyses, interpreted the results, and was the primary author of the manuscript.

5.2 Introduction

Weed competition has been considered to be one of the main biotic constraints limiting crop production worldwide (Oerke 2006). Weeds not only impact global food production, they also indirectly can cause agricultural pollution since herbicides used to control them are the most widely used pesticides globally (Krahmer 2012). Although weed science has traditionally focused on direct weed control, some evidences suggest that many other environmental and crop management practices can affect crop-weed competition (Di Tomaso 1995; Gallandt et al. 1998; Ruiz et al. 2008) and thus could be used to manage yield loss due to weed competition (Ryan et al. 2009; Smith et al. 2010). Therefore, the decisions to apply herbicides based on weed density threshold levels may not be relevant to all cropping systems. The theory of plant coexistence based on niche separation (Gause 1934; Silvertown 2004) helps explain how crop management practices influence crop-weed competition. Accordingly, resource partitioning and resource complementary that facilitate coexistence of plants could occur due to many reasons, such as the diversity of growth forms of competing plants (Casper and Jackson 1997; Fridley 2003), plant uptake of different forms of N (Chapin et al. 1993; George et al. 1999; McKane et al. 2002; Pornon et al. 2007) and spatial and temporal diversity in resource pools (Greenlee and Callaway 1996; Theodose et al. 1996; Hooper 1998; McKane et al. 2002). The diversity in crop management practices can enhance niche partitioning among crops and weeds by enhancing the diversity in soil nutrient resources (Smith et al. 2010) thereby reducing competition.

A global interest in alternative sustainable crop management systems has led to the diversity in cropping practices. In particular, organic crop production, which does not utilize agro-chemicals, has become a sustainable alternative to conventional crop production. Organic systems use alternatives to synthetic inputs, including crop rotations, green manure /cover crops and farmyard manure for nutrient-building strategies while weed control is carried out using short-term cultural and mechanical methods combined with long-term crop rotations as alternatives to synthetic inputs. However, sustaining organic crop production with substantial yields while excluding synthetic inputs has been the key challenge faced by the organic industry. Meta-analysis of organic versus conventional cropping systems worldwide found 5-35% lower yields in organic systems compared to conventional systems, depending on the crop type and system (Seufert et al. 2012; Ponisio et al. 2015). Soil nutrient deficiencies (Waldon et al. 1998; Barberi 2002; Kirchmann et al. 2007) and high weed density (Entz et al. 2001; Posner 2008) associated with organic systems are considered to be the prime causes of low yields. However, although many studies have identified low yields in organic compared to conventional systems (Entz et al. 2001; Ryan et al. 2004; Welsh et al. 2009), some studies have reported either similar or substantially higher yields in organic systems, even with greater weed abundance (Delate and Cambardella 2004; Davis et al. 2005; Hiltbrunner et al. 2008; Ryan et al. 2010). This suggests that despite higher weed densities in some organic systems, they have better crop tolerance to weed competition and hence, lower yield loss.

Differences in crop tolerance to weed competition among cropping systems can be explained by their differences in resource pool diversity (Smith et al. 2010). Accordingly, a management system with diverse inputs creates diversity in soil nutrient resources due to the differences in nutrient dynamics and resource pools. This diversity in soil nutrient resources can create niche separation among plants, thereby reduce competition for resources. Greater soil organic matter in organic systems (Clark et al. 1998; Drinkwater et al. 1998; Liebig and Doran 1999; Mäder et al. 2002; Marriott and Wander 2006), improved soil conditions (Bauer and Black 1994; Liebman and Davis 2000) and altered nutrient dynamics due to different sources of nitrogen (Dyck et al. 1995) under organically managed soils may enable crops to sustain greater weed density without sacrificing yields (Di Tomaso et al. 1995; Ryan et al. 2009). According to Smith et al. (2010), resource pool diversity can be created by rotating crops with different functions, such as legume vs. non-legume, broad leaf vs. grass, annual vs. perennial and mycorrhizal vs. amicorrhizal. With the increase in crop diversity in the rotation, the quality and the quantity of crop residue returning to the soils will differ. Because residues of various crops have different capacities to supply nutrients to the soil (Schoenau and Campbell 1996), varying the crop residues directly influences the buildup of soil organic matter and the availability and timing of nutrients via mineralization (Jarvis et al. 1996). Furthermore, cropping intensity and diversity also influence soil microbiological diversity, activity and biomass (Lupwayi et al. 1998, 1999), which can further enhance soil resource pool diversity.

Cropping systems in the Canadian prairies have been transformed from tillage-based high input systems with wheat (*Triticum aestivum* L.)-wheat-fallow crop rotations to no-till conventional systems and/or organic systems with more intensified and diversified crop rotations, including cereals, pulses, oilseed crops and perennial forage crops (Lafond et al. 1993; Dhuyvetter et al. 1996; Zentner et al. 2001, 2002; Entz et al. 2002) in both input systems. Organic systems in the prairies are mainly grain-based and rely more on green manure crops than farmyard manure to manage weeds and soil fertility. Although a few studies have found that crop-weed competition can be affected by the chosen crop management practices or soil organic matter, no researchers have studied yield loss due to contrasting crop rotations in organic and conventional systems. Even though Smith et al. (2010) proposed the resource pool diversity hypothesis, it has never been empirically tested. Furthermore, due to the differences in crop management among regions and climatic differences, enhanced crop tolerance to weed competition due to crop management may not be universal. Hence, a micro plot study was carried out within the long-term (18 year) diverse cropping systems experiment at Scott, Saskatchewan, Canada (Brandt et al. 2010) to directly evaluate crop yield loss due to weed competition in cropping systems in the prairies. Therefore this study hypothesized that weed density and weed biomass are higher in organic than no-till conventional systems; hence, crop yields are lower in organic systems. Furthermore, it hypothesized that crop yield loss due to weed competition is lower in a more diverse system (i.e., an organic high diversity rotation with annuals and perennials) compared to a less diverse system (i.e., a conventional low diversity crop-crop-fallow rotation). The main objective of this study was to identify the impact of weeds on crop yields under diverse cropping systems and to identify whether organic and conventional crop rotations have differences in yield losses due to weeds.

5.3 Materials and Methods

5.3.1 Long-term alternative cropping systems study

A long-term cropping system study was established in 1994 at Scott, Saskatchewan (52° 22'; 108° 50', elevation = 713 meters). Scott is near the geographic center of the Canadian prairies, in the Dark Brown soil zone between the semi-arid region to the south and the sub-humid region to the north. The details of the experiment were well explained in Brandt et al. (2010); hence, only details particular to this study will be explained here.

The experimental site consisted of 16 ha. The experimental design was a four-replicate split-split plot. Main plots measured 76.8 m × 140 m, sub-plots were 76.8 m × 40 m, and cropping phase plots were 12.8 m × 30 m. Main plots had three levels of inputs, and sub-plots had three levels of cropping diversity (crop rotations). Each crop rotation had six sub-sub plots (six crop phases) to represent a 6-year rotation cycle. The organic (ORG) systems used non-chemical pest control and nutrient management strategies, and the conventional no-till (CONV) systems referred to as the "reduced input systems" in the original study (Brandt et al. 2010) used integrated, long-term management of pests and nutrients with chemicals used as a supplement along with other management practices. High input systems with conventional tillage used pesticides and fertilizers, according to conventional recommendations associated with pest thresholds and soil tests. For this study, we used CONV and ORG systems only, since most farmers in the Canadian Prairies no longer choose high input systems. Each cropping input system had three levels of crop rotation diversity, with the crop rotations differing between systems to reflect common crops and practices for each system. The low crop diversity system (LOW) consisted a rotation of fallow-crop-crop. Medium diversity rotation (MEDIUM) also referred to as the diversified annual grain system in the original study consisted of cereal, oilseed and pulse crops. The high diversity rotation (HIGH) referred to as the diversified annual perennial system in the original study used a mix of grain and forage crops. Table 5.1 lists all the crop phases in each cropping system. All crops were spring seeded (Brandt et al. 2010).

Table 5.1. Crop phases of organic (ORG) and no-till conventional (CONV) cropping systems used in the Alternative Cropping Systems trial at Scott, Saskatchewan.

Input	Crop rotation	Crop Phases
CONV	LOW	GM fallow-**Wheat**-Wheat-Fallow-Canola-Wheat
	MEDIUM	Canola-Wheat-Pea-Barley-Flax-**Wheat**
	HIGH	Canola-**Wheat**-Barley-Alfalfa-Alfalfa-Alfalfa
ORG	LOW	GM fallow-**Wheat**-Wheat-GM fallow-Mustard-Wheat
	MEDIUM	GM fallow-**Wheat**-Pea-Barley-GM fallow-Mustard
	HIGH	Mustard-**Wheat**-Barley- Alfalfa-Alfalfa-Alfalfa

± GM-green manure

* Crop phases highlighted were only used in the current study

5.3.2 Micro-plot experiment

To test our specific hypotheses, a micro-plot study was carried out in 2011 and 2012 within the existing long-term study (Figure 5.1). Four additional sub-plots (2 x 3 m) were established within a selected wheat phase of all rotations in CONV and ORG treatments, making it a split-split-split plot design with four replicates (Figure 5.1). The split-split-split plot factors included the following four weed competition levels: no-weed management; weed-free (hand weeded); standard weed management; and a model weed treatment, where tame oat (*Avena sativa* L.) was seeded at a 1:1 ratio with the wheat seeding rate.

The four micro-plots were established after the wheat crop had been seeded in the split-split-plots in the main experiment. Spring wheat variety AC Lillian was seeded in the ORG and CONV systems on May 14, 2011 and May 16, 2012. Both treatments were seeded at a target plant density of 300 plants m^{-2}. The ORG treatments were seeded using a 15-cm double disk press drill and had 15-cm inter-row spacing. The CONV systems were seeded using a hoe drill and had 25-cm inter-row spacing. The model weed treatment was established by seeding tame oat variety CDC Dancer at 300 plants m^{-2} after the wheat crop had emerged. Oat was seeded using a double disk cone seeder in between wheat rows. All weeds were removed by hand in both the weed-free and the model weed treatments. The same standard weed control practices were applied on to wheat crops in both the main and in the micro-plot. When herbicides were applied to the standard weed control treatment in micro plots, a polythene cover was laid over the rest of the micro-plots in order to prevent the herbicides being applied to the other micro-plots. When the organic standard treatment in micro-plots was hoed, the tractor drove through the rest of the micro-plots with hoes raised in order to impose similar tractor effect on all other micro-plots.

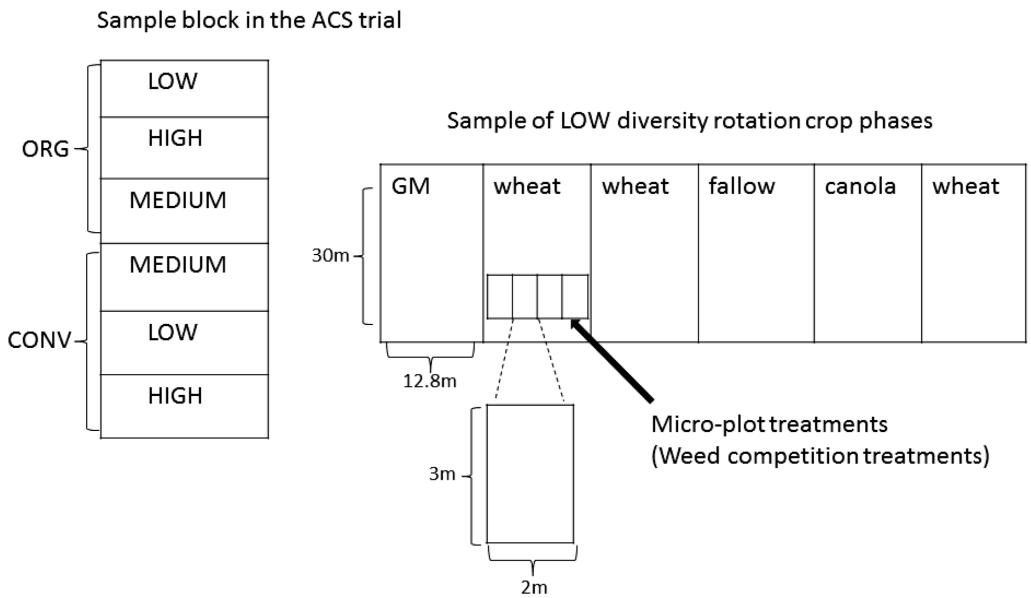

Figure 5.1. Schematic representation (not to scale) of the field layout of a sample main plots, split plots and split-split plots (micro-plot study) in the ACS trial at Scott, Saskatchewan, Canada.

5.3.3 Standard weed management

5.3.3.1 Pre-emergence weed control

In the ORG systems, fall tillage was used to control fall-germinating winter annual weeds and encourage early spring weed and volunteer crop germination. In the fall of 2010 and 2011, all organic treatments were cultivated with a sweep-type cultivator and followed by a tine harrow and harrow packing for levelling. During the following spring (May) in each year, another harrowing and harrow packing was carried out before seeding. In the CONV systems, pre-planting tillage was typically done with harrows to spread crop residues and to prepare a seedbed after fall tillage when alfalfa was terminated in the HIGH system. Control of winter annual weeds in the CONV systems was achieved by applying Saflufenacil (Heat WG, 700 g kg^{-1}, WSG, BASF Canada) at a rate of 25 g ai ha^{-1} and Glyphosate (Roundup Ultra 2, 540 g l^{-1}, SN, Monsanto Canada) at a rate of 900 g ai ha^{-1} in late fall. Spring pre-seed weed control was carried out with Bromoxynil (Brotex 240, 240 g l^{-1}, EC, IPCO Ltd.) at a rate of 280 g ai ha^{-1} and Glyphosate (R/T 540, 540 g l^{-1}, SN, Monsanto Canada) at a rate of 540 g ai ha^{-1}.

5.3.3.2 Post emergence weed control

In-crop weed control was carried out with registered graminicides and broadleaf herbicides determined by the species present and their density. Therefore, herbicides and the rates were based on a plot-to-plot basis. If grass weeds were present, plots were treated with Pinoxaden (Axial BIA, 50 g l^{-1}, EC, Syngenta Canada) at a rate of 60 g ai ha^{-1} or Pyroxsulam (Simplicity, 50 g l^{-1}, OD, Dow AgroSciences) at a rate of 15 g ai ha^{-1}. For annual broadleaf weeds, plots were treated with a pre-mix of Florasulam + MCPA ester (Frontline XL, 5 g l^{-1} + 280 g l^{-1}, EC, Dow AgroSciences) at a rate of 5 + 345 g ai ha^{-1} or Clopyralid + MCPA ester (Curtail-M, 50 g l^{-1} + 280 g l^{-1}, EC, Dow AgroSciences) at a rate of 100 + 560 g ai ha^{-1}. Post-emergent weed control was carried out in ORG systems using a flexible tine-harrow and a rotary hoe in 2011 and 2012, respectively. Multiple passes were carried out based on weed emergence.

5.3.4 Data collection

Plant counts were taken after emergence by placing two 0.25 m^2 quadrats at the front and back of each micro-plot. Each quadrat included three wheat rows. Oat plant (model weed) counts were also taken in the model weed treatment. Weed counts of weedy and standard treatments were taken one week after application of a particular standard weed control treatment in organic and conventional rotations. Weed counts were taken by placing four 0.25 m^2 quadrats at the front and back of each plot. Each quadrat included three wheat rows. After maturity, samples of aboveground crop and weed biomass were collected from all the sub-sub-plots by placing two 0.25 m^2 quadrats at the front and back of each plot; these samples were then separated. In the model weed treatment, tame oat biomass and crop biomass were sampled. Crop, weed and tame oat biomass samples were then bagged separately and oven dried at 60–70 °C for 48h. After drying, the biomass was then weighed. At crop maturity, the wheat was hand harvested placing two 0.25 m^2 quadrats at the front and back of each micro-plot. The wheat was then threshed using a combine harvester and cleaned using a dockage tester; the final air-dried grain was then weighed. Yields were recorded at 13% moisture level.

5.3.5 Data analysis

Total weed density, weed biomass, oat biomass, crop biomass, grain yield and yield loss data were tested for the assumptions of analysis of variance (ANOVA). Yield loss was determined using the difference between weedy yield and weed-free yield as a ratio of the weed-free yield of the particular treatment. Appropriate transformations were carried out to meet the assumptions of ANOVA using Levene's Test and visually observing the residuals. The data were then analyzed using MIXED models in SAS 9.3 (SAS Institute, 2011) as a split-split-split plot design. Year, block, block by input and year by all the treatment (input and rotation) interactions were considered random, while all the treatments were considered fixed factors. Data analysis was carried out by combining the data collected over both years. Because there were no significant random year by treatment interactions for all the variables, the results were presented as mean values from both years. Crop density was tested as a corvariate, and analysis of covariance (ANCOVA) was used to analyze grain yield and weed biomass. Since the covariate was not significant, the data were analyzed using ANOVA. Similarly, oat (pseudo weed) density was used as a covariate when analyzing crop and oat biomass from the pseudo weed treatment. Since the covariate was not significant, ANOVA was considered for the following analysis. Means were compared using the least significant difference (LSD) test, and were declared significant when $P < 0.05$.

5.4 Results

5.4.1 Grain yield

Grain yield was mainly determined by the input by weed competition interaction (Table 5.2). In all weed-free, no-weed management, or standard weed management conditions, grain yield was low in organic (ORG) input systems compared to the no-till conventional (CONV) systems (Figure 5.2).

Under standard weed management conditions, grain yield was 44% lower in ORG systems compared to CONV systems. Interestingly, under high uniform weed competition conditions (model weed treatment), the ORG and CONV systems had similar grain yield (Figure 5.2). Under natural weed competition conditions, yields for the ORG and CONV systems were reduced by only 18% and 13%, respectively (Figure 5.2). Under model weed competition, the CONV systems had a greater yield loss (56%) compared to the ORG systems (41%). However, when the yield loss was statistically analyzed as a separate variable, no differences were found for relative yield loss either under natural weed competition or under model weed competition (Table 2). Similarly, there were no differences in yield loss among crop diversity levels or for their interactions with input levels (Table 5.2). There was also a trend $P = 0.07$ for an interaction between the input and crop rotation for grain yield (Table 5.2). Grain yield tends to be higher CONV-LOW and CONV-HIGH rotations than all the other rotations (Figure 5.3). The organic MEDIUM rotation tend to be similar to CONV-MEDIUM rotation.

Table 5.2. ANOVA for the effect of input, rotation and weed competition on weed density, natural weed biomass, model weed biomass, grain yield and yield loss under natural weed competition and under model weed competition assessed at Scott in 2011 and 2012. The values indicate probability.

Treatment	Weed Density±	Natural Weed Biomass±	Model Weed Biomass	Yield±	Yield Loss (model weeds)†	Yield loss (natural weeds)†
Input (I)	0.0063	0.7338	0.0296	0.0003	0.2184	0.5281
Rotation (R)	0.1696	0.0012	0.017	0.8985	0.6667	0.8333
Weed competition (WC)	0.0129	0.0003	NA	0.0118	NA	NA
I x R	<0.0001	0.2021	0.0481	0.0700	0.9472	0.4547
I x WC	0.0979	0.0006	NA	0.0011	NA	NA
R x WC	0.2878	0.7632	NA	0.7474	NA	NA
I x R x WC	0.0257	0.7228	NA	0.5051	NA	NA

± denotes data 4th root transformed before analysis.

† denotes data square root transformed before analysis.

NA denotes not applicable.

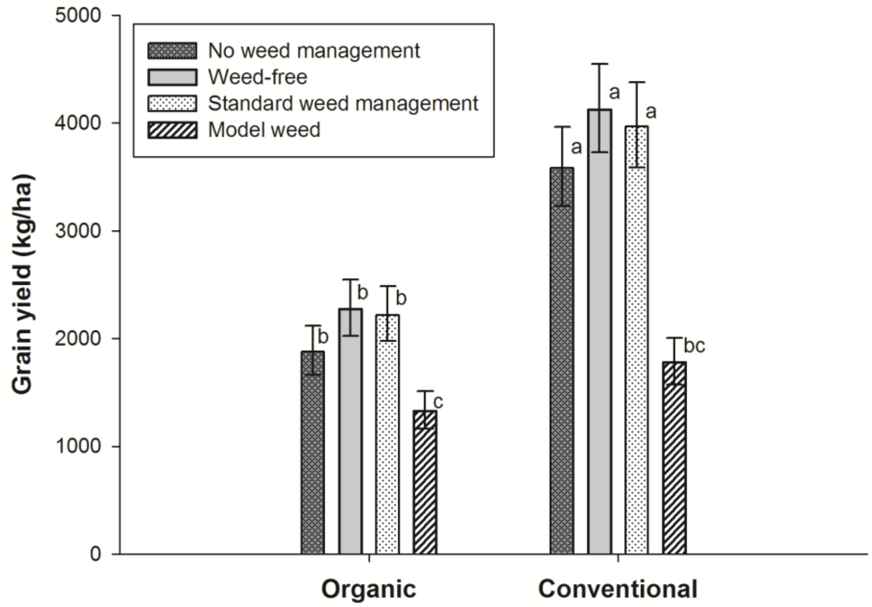

Figure 5.2. Effect of input level (ORG and CONV cropping systems) and weed competition (no weed management, weed-free, standard weed management and model weed) on grain yields of spring wheat (kg ha^{-1} at 13% moisture content) assessed in 2011 and 2012. Error bars represent back-transformed standard errors of the treatment means (pooled across two years with n=4). Comparisons made between treatments with similar letters indicate no significant difference at LSD < 0.05.

5.4.2 Weed density and weed biomass

Weed densities varied among cropping systems depending on the weed competition treatments (micro-plot treatments) (Table 5.2). Standard weed control treatment in CONV systems (i.e., application of herbicides) reduced weed densities in all CONV rotations (HIGH, MEDIUM and LOW) whereas in the ORG systems, standard organic weed control treatment (i.e., in crop harrowing and hoeing) effectively reduced weed densities only in the LOW and MEDIUM rotations (Figure 5.4). The ORG-HIGH rotation had the highest weed density, irrespective of the weed control treatment. Specifically, in the ORG systems, under standard weed management conditions, weed densities in the HIGH rotation were four times greater than in the LOW rotation and three times greater than in the MEDIUM rotation. In the CONV systems, weed density was highest in the MEDIUM rotation, both under the standard weed management and under no weed management conditions.

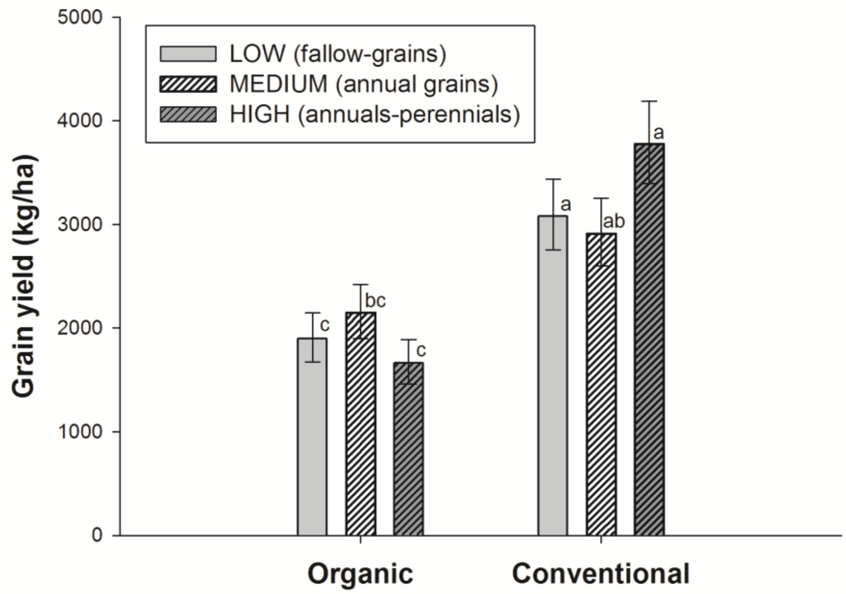

Figure 5.3 Effect of input level (ORG and CONV cropping systems) and crop rotation (LOW, MEDIUM and HIGH) on grain yields of spring wheat (kg ha^{-1} at 13% moisture content) assessed in 2011 and 2012. Error bars represent back-transformed standard errors of the treatment means (pooled across two years with n=4). Comparisons made between treatments with similar letters indicate no significant difference at LSD < 0.05.

With standard weed control treatments in both systems and irrespective of crop rotation, the ORG systems had four times more weed biomass than in the CONV systems (Figure 5.5). Under no weed management conditions, the CONV systems tended to have greater weed biomass (P = 0.064) compared to the ORG systems. Furthermore, in the CONV systems, weed biomass in the no-weed management treatment was 14 times greater than in the standard (herbicide) weed management treatments, indicating that even with long-term herbicidal weed control in conventional systems, weeds still occur when the herbicides are not being applied. Importantly, there was no difference in weed biomass between the no-weed management and the standard weed management treatments in ORG input systems, implying that weed control strategies in organic systems are relatively ineffective.

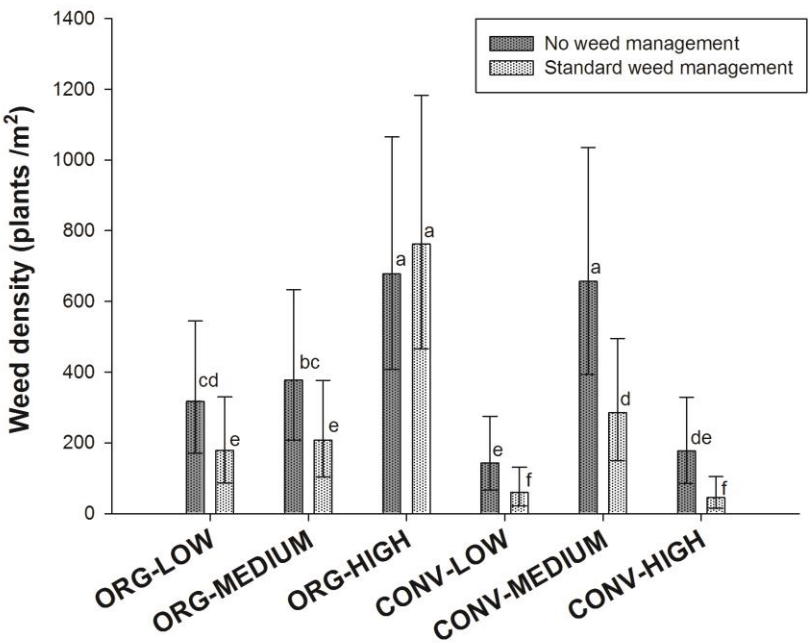

Figure 5.4. The effect of input level (ORG and CONV cropping systems), crop rotation (LOW, MEDIUM and HIGH) and weed management (no weed management, weed-free, standard weed management and model weed) on weed density assessed in 2011 and 2012. The bars are back transformed lsmeans. Error bars represent back-transformed standard errors of the treatment means (pooled across two years with n=4). Comparisons made between treatments with similar letters indicate no significant difference at LSD < 0.05.

Crop rotation had a significant effect on weed biomass, regardless of the input or weed competition treatments (Table 5.2). The LOW diversity rotations had five times greater weed biomass than the HIGH diversity (annual-perennial) rotations (Figure 5.6). The MEDIUM diversity (continuous annual grains) rotations had intermediate weed biomass compared to the LOW and HIGH rotations (Figure 5.6). These differences in weed biomass were not due to the differences in weed density, as weed density was greatest in the ORG-HIGH rotation and lowest in the CONV HIGH and CONV-LOW rotations (Figure 5.4). There was an input by rotation interaction for the model weed (Table 2). Among all the systems, the HIGH diversity rotation in the ORG systems had the lowest model weed biomass (Figure 5.7).

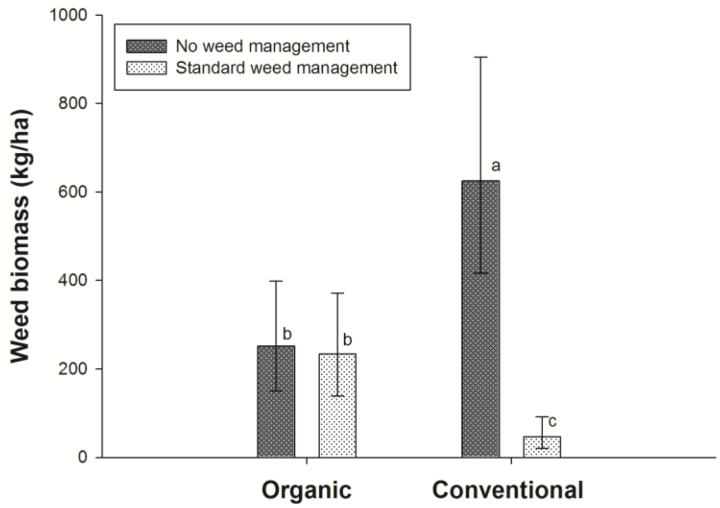

Figure 5.5. Effect of input level (ORG and CONV cropping systems) and weed competition (no weed management, standard weed management) on weed biomass assessed in 2011 and 2012. The bars are back-transformed lsmeans. Error bars represent back-transformed standard errors of the treatment means (pooled across two years with n=4). Comparisons made between treatments with similar letters indicate no significant difference at LSD < 0.05.

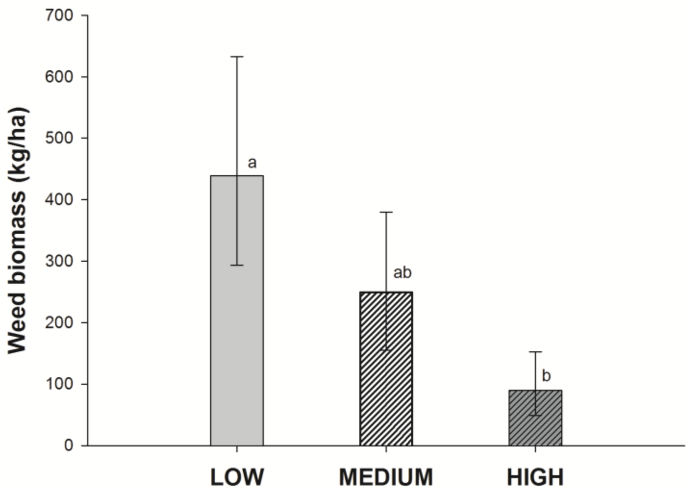

Figure 5.6. The effect of crop rotation (LOW, MEDIUM and HIGH) on weed biomass. The bars are back-transformed lsmeans of average weed biomass across no weed management and standard weed management treatments in 2011 and 2012. Error bars represent back-transformed standard errors of the treatment means (pooled across two years with n=4). Comparisons made between rotations with similar letters indicate no significant difference at LSD < 0.05.

5.4.3 Total plant biomass

Analysis of total plant biomass (crop and weed) from both no-weed management and the model weed treatments indicated a significant input by rotation interaction (P = 0.002 and P = 0.0006, respectively; data not shown). This implies that cropping systems differ in overall soil productivity as determined by the input by rotation interaction. Organic rotations had low plant biomass (low productivity) compared to conventional rotations under natural weed competition (no weed management treatment) (Figure 5.8A). Meanwhile, under model weed competition, ORG-HIGH systems had the least plant biomass production (Figure 5.8B).

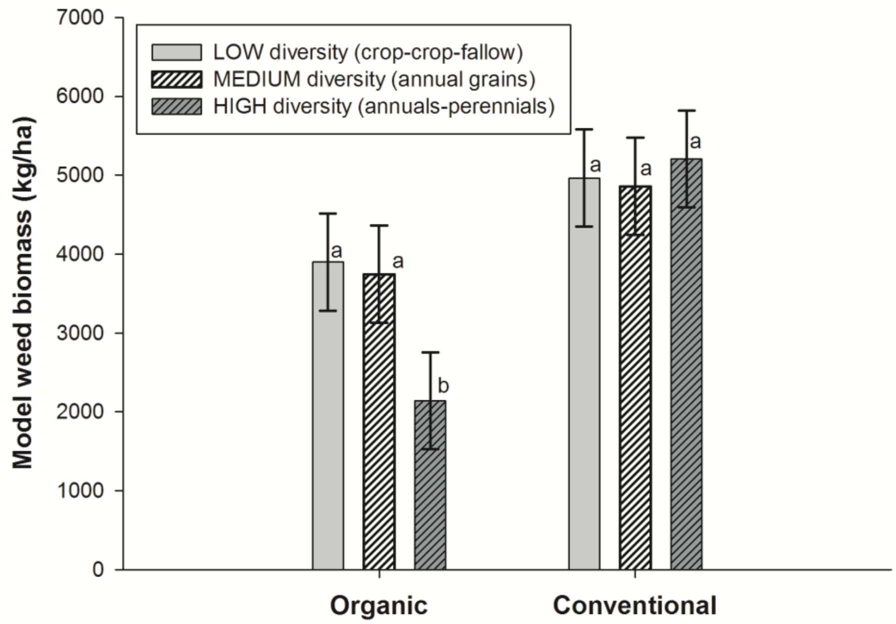

Figure 5.7. The effect of input level (ORG and CONV cropping systems) and crop rotation (LOW, MEDIUM and HIGH) on model weed (tame oat) biomass. The bars are lsmeans of averaged model weed biomass in 2011 and 2012. Error bars represent standard errors of the treatment means (pooled across two years with n=4). Comparisons made between treatments with similar letters indicate no significant difference at LSD < 0.05.

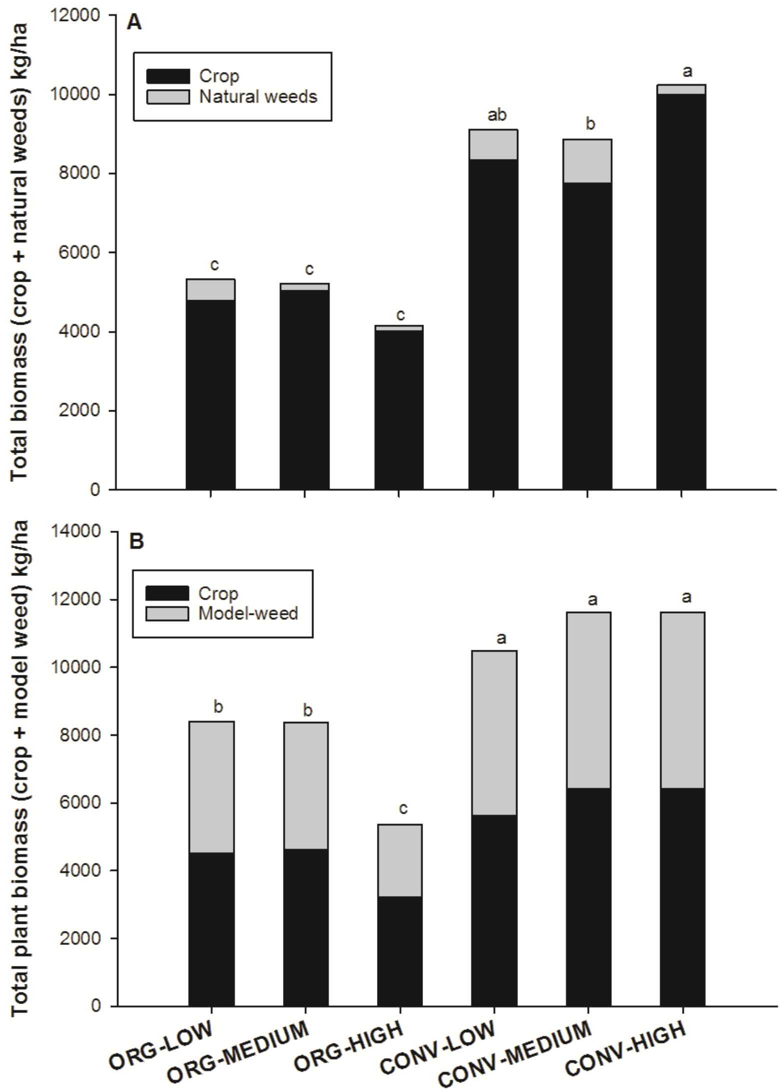

Figure 5.8. The effect of input level (ORG and CONV cropping systems) and crop rotation (LOW, MEDIUM and HIGH) on (A) crop + natural weed biomass and (B) crop + model weed biomass, assessed in 2011 and 2012. Comparisons made between treatments with similar letters indicate no significant difference at LSD < 0.05.

5.5 Discussion

This study revealed that the natural weed density and weed biomass were four times higher in the organic than conventional systems and it was in accordance to many others (Davis et al. 2005; Ryan et al. 2009) who found similar differences. It is widely accepted that crop yield decreases with increasing weed density (Cousence 1985; Stoller et al. 1987; Wilson and Wright 1990). However, we did not find such a relationship with weed density and crop yields. Similarly, in this study the cropping systems which had high weed density at early crop growth stages did not necessarily have high weed biomass at the later stages either. Currently, most of the economic thresholds for weed control are estimated using models with biological and ecological aspects of weeds; however, these can be overestimations as none of these models consider crop management practices that can alter weed competition, such as N status (Tollenaar et al. 1994; Cathcart and Swanton 2003; Evans et al. 2003) and soil organic matter amendments (Dyck et al. 1995; Liebman and Davis 2000; Davis and Liebman 2001). Perhaps this lack of relationship between weeds and crop yields is because the natural weed density and biomass in this study were low. Nevertheless, based on our findings, weed density should not be the sole predictor of crop-weed competition.

Low natural weed biomass could be the main reason for not identifying crop yield loss in both organic and conventional rotations compared to their particular weed free treatment. Even though the natural weed competition was not strong enough to cause yield differences, the model weed competition reduced grain yields drastically in both organic and conventional systems. Since the model weed biomass was similar among all systems except in ORG-HIGH, we could expect similar weed competition for all systems but ORG-HIGH. However, we did not find differences in yield loss among different input levels or among crop rotations under similar weed competition. Therefore, we do not have enough evidence to accept the hypothesis that differences in cropping systems results in differences in yield loss due to weed competition. Hence, we do not have evidence to support the resource pool diversity hypothesis (Smith et al. 2010) for these grain-based cropping systems in the prairies.

The lack of evidence for the differences in crop-weed competition in organic and conventional in this study compared to other studies (Ryan et al. 2010, 2009) could be due to many reasons, and particularly due to the differences in cropping systems in terms of crop rotations, type and the intensity of tillage and soil amendments used to enhance soil fertility. Because of the differences in the quantity and quality of organic matter in most organic systems (due to crop rotations and other external input sources of organic matter), the soil resource pools in these systems are expected to be highly diverse. However, although the organic systems in this study used diverse crop rotations, excessive tillage can deplete organic matter and its subsequent benefits (Franzluebbers et al. 1999; Weil and Magdoff 2004; Grandy et al. 2006). Therefore, a no-till conventional system with similar crop rotation can conserve more organic matter than a tillage-based organic rotation. In the review of studies supporting the resource pool diversity hypothesis, Smith et al. (2010) compared conventional tillage vs. tillage-based organic systems. In those studies, tillage-based organic systems may have been better than the tillage-based conventional systems in regards to soil-related factors. In contrast, our study compared no-till conventional system to a tillage-based organic system with similar crop rotations in both. Hence, no-till conventional system in this study may be better compared to tillage based organic system in-terms of soil resource pool diversity.

Lower soil productivity in these organic systems than the conventional systems can be another reason for not identifying greater crop tolerance to weed competition (low yield loss) in organic. Lower crop yields in organic even in the absence of weeds found in this study confirm that low yields are due to soil related factors than weed competition. Furthermore, we found lower total plant biomass production in organic confirming lower soil productivity. Soil test phosphorus was typically deficient in the cropping systems in this long-term cropping systems study (Malhi et al. 2009), and is generally deficient across Canadian organic farms (Entz et al. 2001; Martin et al. 2007; Knight et al. 2010). The main reason for the lack of soil fertility in organic systems in this region may be the inadequate use of farmyard manure as a soil fertility source due to the lack of availability (Shirtliffe et al. 2005). A study in Nebraska identified that animal manure-based organic systems were superior in the total phosphorus balance compared to forage-based organic systems (Roberts et al. 2008). In a similar study in the USA, a manure-based organic system was found to have better yields than a conventional system, but the legume-based system was not found to be better than the conventional system (Ryan et al. 2009). The diversity in soil resources and productivity could be higher in some American organic cropping systems because the total amount of nutrients applied to these systems is high or even higher than the nutrients applied to comparable conventional systems (Porter et al. 2003; Denison et al. 2004; Sanchez et al. 2004; Pimentel et al. 2005; Teasdale et al. 2007). Hence, most researchers reporting organic systems with yields similar to or greater than conventional systems have studied organic systems that used large amounts of farmyard manure. Therefore, from the results of this study, we speculate that low soil fertility in terms of available N and P in organic cropping systems may have confounded the advantages of soil quality related factors normally expected in organic systems.

The differences observed in weed biomass among crop rotations could be due to the differences in soil productivity. Low weed biomass in a particular cropping system could be due to low weed density, better weed suppression or lower soil fertility. We did not find any relationship between weed density and subsequent weed biomass for any of the cropping systems. Similarly, even with its greater weed density, the organic systems had lower weed biomass than the conventional systems. Since total plant biomass (both plant and weed biomass) was low in the organic systems, and particularly low in the organic HIGH system, we can conclude that low weed biomass found in HIGH diversity rotations could be due to low crop productivity rather than due to greater weed suppression. This low productivity, particularly in the ORG HIGH rotations, may be due to the three-year perennial alfalfa crop (Campbell et al. 1993; Bell et al. 2012). Therefore, this study further shows that increasing crop diversity with perennial crops may cause long-term productivity issues.

Low crop yields due to poor soil fertility were found to be the major problem in organic rotations in this study. The overall low soil fertility in the organic systems studied here probably negated any of the expected benefits associated with organically managed soils, such as higher tolerance to weed competition. Enhancing the soil fertility by increasing the amount of soil organic matter would be able to increase soil productivity as well as increase crop tolerance to weed competition. As observed in some other systems, external application of farmyard manure can be a potential solution. Yet, extensive use of farmyard manure to enhance soil fertility is not a practical or sustainable solution for most organic farms worldwide, as they usually do not have integrated livestock. Further, those organic farms that do have livestock do not produce the substantial amounts of manure needed to raise soil fertility. However, this study did not reveal the exact soil related factors hindering crop yields. Hence, it would be intriguing to determine the yield loss due to weed competition under similar soil nutrient levels in these organic and conventional cropping systems.

5.6 Conclusions

This study provides a comprehensive understanding of how weeds impact grain yields under diverse cropping systems. Weed densities were higher in organic compared to conventional systems and in the annual-perennial rotation. However, there was no direct impact of weed densities on reducing crop yields. Despite an absence of weed competition, organic systems had substantially lower crop yields than conventional systems, confirming that low yields in organic systems are not due to weed competition but are due to the other soil-related factors. This study also found no differences in crop yield loss between organic and conventional systems due to weed competition, indicating no difference in crop-weed competition between the systems. Increasing the crop diversity and the intensity of rotations did not increase crop yields, suppress weeds or reduce yield loss in either cropping system. In fact, the overall productivity of the system has been reduced, particularly, when using perennial crops in organic systems. Therefore, both resource diversity and overall productivity of the system might be needed to enhance in order to increase the crop tolerance to weed competition.

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Prologue (Chapter 6)

Understanding the influence of weed community dynamics on crop yields in cropping systems is a challenging task as multiple factors can influence crop yields. The first two chapters (chapter three and chapter four) found that weed abundance and composition is different among contrasting cropping systems in the ACS trial. Chapter five found that even when weeds are absent, wheat yields are lower in organic compared to no-till conventional system (RED) in the ACS study, possibly because of soil fertility related factors. Other studies have found that soil available N and P can be the most limiting in organic systems in these regions. Furthermore, chapter five also found that yield loss due to weed competition did not differ between organic and no-till conventional systems in the ACS trial, leading into a conclusion that soil resource diversity is not higher in organic compared to conventional systems. Therefore, we speculated that overall low soil fertility in these grain based organic systems are causing poor crop yields and poor crop tolerance to weed competition. According to all these studies, I hypothesize that these organic systems are yield limited due to lower plant availability of soil N and P. Furthermore, I hypothesize that when soil available N and P is not limiting, crop yields in organic systems could be greater and crop yield loss due to weed competition is less than the no-till conventional systems. The work presented in chapter six attempts to test these hypotheses using a green-house study with the soils obtained from the ORG rotations and RED rotations in the ACS study. In this chapter, for the convenience, the RED input system was re-named as no-till conventional (CONV) and the three crop rotations were re-named as LOW, MEDIUM and HIGH for Low, diversified annual grains and diversified annual perennial rotations respectively.

6.0 DOES APPLICATION OF FERTILIZERS TO ORGANICALLY MANAGED SOILS INCREASE CROP BIOMASS YIELD AND INCREASE CROP TOLERANCE TO WEED COMPETITION THAN THE NO-TILL CONVENTIONAL SOILS?

6.1 Abstract

Well managed organic soils are believed to have higher crop yields than conventionally managed soils due to the greater soil quality and the ability to tolerate weed competition. However, the scarcity of the available soil N and P in some organic systems may confound such soil quality related benefits. We hypothesize that when soil N and P are not limiting, organic crop rotations with high diversity have less yield loss (better crop tolerance) than the no-till conventional systems with low diversity rotations. A greenhouse study was carried out in Saskatoon, Canada, using long-term (18 year) organically managed soils (ORG) and no-till conventional soils (CONV) with three crop rotation diversities (low, medium and high) to compare the crop tolerance to weed competition and crop biomass productivity under standard nutrient management conditions and under excess supply of mineral N and P in weedy and weed free conditions. Weed biomass was similar between ORG and CONV systems under non-fertilized conditions, but CONV had 14% greater weed biomass when excessive N and P were supplied. Crop biomass loss due to weed competition was similar for all cropping systems under both fertilized and non-fertilized conditions, indicating no difference in crop tolerance to weed competition. Under non-fertilized conditions, the crop biomass was 43% lower in ORG compared to CONV, and even after mineral N and P was applied, organic systems showed less (16%) crop biomass than CONV. When excessive amounts of N and P were applied, crop biomass were increased by 50% and 69% in organic and conventional systems respectively. Plant available N and P were the most yield limiting factors found in the organic rotations. There was no greater yield benefits or crop tolerance to weed competition compared to no-till conventional systems indicating that organic soils do not necessarily have soil quality related advantage in suppressing weeds.

6.2 Introduction

Feeding the ever increasing world population with sustainable crop production systems has become the most challenging tasks for the global agriculture at present. Organic farming systems are believed to have a vital role towards reaching the sustainability in crop production. Organic systems rely on enhancing the soil quality and soil health via optimized ecological based farming practices while foregoing the use of agro-chemicals to produce crops. Some organically managed soils are known to have greater soil quality due to better chemical, physical and biological properties (Bolton et al. 1985; Mäder et al. 2002; Mulder et al. 2003; Birkhofer et al. 2008; Lynch et al. 2012) which determines nutrient availability, structure and the biological functions in a soil.

Soil organic matter (SOM) is the principal component of soil fertility (Altieri 1983; Lal 2004) and an overwhelming body of research has identified that organic systems have greater amounts of SOM due to the use of farmyard and green manures (Drinkwater et al. 1998; Clark et al. 1998, Liebig and Doran 1999; Mäder et al. 2002). Therefore, proponents of organic farming believe that soil fertility in organic systems is generally higher than the conventional systems (Reganold, 1988; Reganold et al. 1993; Teasdale et al. 2007). Organic cropping systems with diverse crop rotations particularly perennial forage crop rotations were found to have better soil quality characteristics than conventional systems (Daroub et al. 2001; Karlen et al. 2006). Referable to the above soil fertility benefits, some studies found either similar or higher crop yields in organic compared to conventional systems (Delete and Cambardella 2004; Davis et al. 2005; Smith et al. 2007; Hiltbrunner et al. 2008; Ryan et al. 2010).

In addition to the direct soil quality related yield benefits of organic farming, Smith et al. (2010) proposed that crops grown in organically managed soils can tolerate greater weed competition than in conventional soils due to the diversity of soil resources and differences in nutrient dynamics which enable niche separation among crop and weeds. Low competition among plant species due to resource partitioning in terms of available plant nutrient forms, particularly organic N (Bol et al. 2002; Ashton et al. 2010) and inorganic N (Teyker 1992; Salas et al. 1997) were identified. Accordingly, Poffenbarger (2015) found that there is an over yielding effect in crop-weed mixture under N limited conditions compared to their monoculture yields indicating N resource partitioning. Therefore, some organic systems have been found to have either similar or greater yields even with high weed abundance (Delate and Cambardella

2004; Davis et al. 2005; Smith et al. 2007; Hiltbrunner et al. 2008; Ryan et al. 2009). Yet, in a greenhouse study Poffenbarger et al. (2015) was unable to identify any cropping systems effect on over yielding of crop-weed mixture than their monoculture due to soil N resource partitioning. However, Ryan et al. (2010) identified that crop-weed competition relationships differ between organic and conventional systems. Therefore, these soil related properties found to be highly different among cropping systems.

Even though some studies found higher crop yields in organic systems, most other studies found low crop yields compared to conventional systems (de Ponti et al. 2012; Seufert et al. 2012; Ponisio et al. 2015). It is believed that the soil nutrient deficiencies, particularly N and P (Waldon et al. 1998; Berry et al. 2002; Kirchmann et al. 2007) and high weed density (Entz et al. 2001; Porter et al. 2003; Posner, 2008) in organic systems are the prime causes for lower yields compared to conventional systems. High crop yields and better crop tolerance to weed competition due to the practice of organic farming was not found in grain-based organic cropping systems compared to conventional systems in the Canadian prairies (Chapter five). Crop yields were found to be significantly lower and therefore crop-tolerance to weed competition was not identified in that study. Lower crop yields and reduced tolerance to weed competition in grain based organic cropping systems could be due to the lack of readily available nutrients which can hinder the beneficial soil related properties that ideally expected in most of the organic systems (Chapter five). Organic cropping systems in the Canadian prairies rely mainly on the nitrogen fixing legumes to supply nitrogen exported with the crop at harvest. Even though farmyard manure is considered a rich source of nutrients (Schoenau et al. 2010), the availability of farmyard manure is limited in the prairies due to the majority of farms in the region being grain-based (Shirtliffe et al. 2005; Knight et al. 2010). Thus, most organic farms in the region are P and N limited (Entz et al. 2001; Martin et al. 2007; Roberts 2008). Furthermore, a review by Liefeld et al. (2009) found that even though there can be a high amount of organic matter in the soil, organic matter is not converted to plant usable forms efficiently in organic systems. Even though some organic systems are able to supply N from manure in amounts comparable to conventional systems, the timing of availability of N to that of the crop requirement may still hinder the growth (Berry et al. 2002).

Differences in soil fertility, weed competition and crop yields in organic versus conventional systems varies due to differences in crop rotations, inputs, soil and environment.

These differences in crop management and other environmental factors can cause differences in crop productivity over the differences in organic versus conventional systems. Hence, a better comparison of organic and conventional systems for their soil related benefits should be carried out under controlled conditions eliminating the confounding factors. In grain-based organic systems, better crop tolerance to weed competition than conventional systems can be expected when most limiting nutrients are being supplied. Therefore, in this study I hypothesize that grain-based organic cropping systems in the Canadian prairies are yield limited due to the lack of readily available essential nutrients particularly, N and P. Also I hypothesize that when N and P are not limiting, organic crop rotations with high diversity have less yield loss (better crop tolerance) than the no-till conventional systems with low diversity rotations and therefore have high crop yields. These hypotheses were tested in a greenhouse with different fertility and weed competition treatments using soils obtained from a long-term organic and conventional cropping system study with diverse crop rotations.

6.3 Materials and methods

6.3.1 Long-term crop rotation study

A greenhouse pot experiment was carried out in 2012 and 2013 in Saskatoon, Saskatchewan, Canada using the soils obtained from the organic (ORG) and conventional (CONV) input systems from the alternative cropping systems (ACS) trial at Scott Saskatchewan Canada. The details of the alternative cropping system trial can be found in the chapter three and in Brandt et al. (2010). The ACS experiment design was a four replicate split-split plot. Main plots consisted of three levels of inputs. The sub-plots consisted of three levels of cropping diversity (crop rotations). Each crop rotation had six sub-sub plots (six crop phases) with a 6 year rotation cycle. Among input levels, tillage based organic (ORG) system used non-chemical pest control and nutrient management strategies. The conventional no-till (CONV) system referred to as the reduced input system (RED) in the original study (Brandt et al. 2010) used long-term integrated management of pests and nutrients with limited use of chemicals to supplement other management practices. The three cropping diversity levels include low crop diversity rotation (LOW) which is a crop-crop-fallow rotation with cereals and canola, the diversified annual grain rotation (MEDIUM) consisted of cereals, oilseed and pulse crops and the diversified annual-perennial rotation (HIGH) used a mix of grain and forage crops. The crop phases in each cropping system are summarized in Table 6.1. All crops were spring seeded. The details of the crop management practices are given in chapter three.

Table 6.1. Crop phases of no-till conventional and the organic cropping systems in the ACS trial at Scott.

Input	Rotation	Crop phases
Conventional	LOW	GM fallow-**Wheat**-Wheat-Fallow-Canola-Wheat
	MEDIUM	Canola-Wheat-Pea-Barley-Flax-**Wheat**
	HIGH	Canola-**Wheat**-Barley-Alfalfa-Alfalfa-Alfalfa
Organic	LOW	GM fallow-**Wheat**-Wheat-GM fallow-Mustard-Wheat
	MEDIUM	GM fallow-**Wheat**-Pea-Barley-GM fallow-Mustard
	HIGH	Mustard-**Wheat**-Barley-Alfalfa-Alfalfa-Alfalfa

±GM-green manure

*The crop phases used in the current study is highlighted

6.3.2 The Greenhouse study

6.3.2.1 Soil sampling

The greenhouse study was carried out using the soils obtained from the long-term ACS study. Soil sampling was carried out in two random locations in north and south end of the selected wheat plot from each crop rotation in the ACS study in all rotations in CONV and ORG input systems (Table 6.1). Soil sampling was carried out in the early spring in both 2012 and 2013 after snow melt. Intact soil sampling was performed to maintain the physical integrity of the soil profile in each input system. Due to the difficulty of obtaining single soil column at once, it was taken at two steps using two open ended PVC pipe sections (20 cm diameter and 15 cm depth). First, one section of the pipe was pushed into the ground and lifted with the intact soil core. Then the second section of the pipe was placed on the same spot where the first soil core was taken and pushed into the ground to obtain the second section of the intact soil column. After lifting the bottom section from the ground with intact soil core, the first part of the pipe (with intact soil core) was placed on top of the second part and was stacked together by wrapping it with rubber straps and metal clips to hold as a single pot containing a single soil column with 20 cm in diameter and 30 cm in depth. The whole pot was kept on a plastic tray to hold the soil. After sampling, all the pots were transported to a greenhouse.

6.3.2.2 Soil fertility and weed competition treatments

The greenhouse pot experiment was a four-way factorial experiment with two soil fertility treatments, two weed competition treatments, two input systems and three crop rotations. The two soil fertility treatments and the two weed competition treatments were applied to the soils obtained from the two input systems and the three crop rotations in the ACS trial. The two soil fertility treatments were; fertilized (N and P added to both organic and conventional) and non-fertilized (no fertilizer was added). The two weed competition treatments were; weedy and weed-free. These four treatment levels were applied to a selected wheat phase in all the input by rotation combinations (2 x 3) in the ACS trial giving 24 treatments for each replication. Altogether, there were 72 pots (2 inputs x 3 rotations x 2 fertilizer treatments x 2 weed competitions x 3 replicates). All the pots were arranged as a randomized block design with three blocks in which each block represented the particular block in the ACS trial where soil samples being taken. The fertilizer and the weed competition treatments differed slightly for the two years in the amount of fertilizer applied and the number of plants used in a pot.

In 2012, for the CONV rotations, the fertilizer N and P were added based on the previous year fall soil test recommendations for the particular wheat plot in the 0-30 cm soil layer. The objective of adding fertilizer to ORG wheat treatments in 2012 was to bring up the N and P level as much closer to the CONV wheat treatment. For the conventional wheat treatment, the required level of N and P was determined based on the available N and P in the particular wheat plot based on previous year fall soil test and the amount required to obtain the targeted crop yield. For the ORG rotations, fertilizer rates were determined based on the available nutrients in the wheat plots in a particular ORG rotation and using the required N and P levels for the particular rotation in CONV wheat plots to obtain the targeted yield. Therefore, the amounts applied varied based on the particular wheat plot in each system.

The fertilizer treatments in 2013 differed from 2012 in terms of the amounts of fertilizer added. In 2013, the N and P levels were applied two times the recommendation of conventional soils in order to provide excess nutrients for both CONV and ORG. In addition, sulfur fertilizer was applied to all the fertilized treatments as well. Fertilizer rates were calculated for each pot in both ORG and CONV system to bring nutrient levels to 110 N kg ha^{-1}, 55 P kg ha^{-1} and 35 S kg ha^{-1}. In both years all these nutrients were supplied using urea, muriate of potash, and ammonium sulfate fertilizers. All fertilizers were added as a solution in water. A stock solution of 2000 ppm was made for urea and muriate of potash, and 1000 ppm solution was made for ammonium sulfate. The total amount of fertilizer to be applied was split into three applications. The first application was done just before transplanting, the second in six weeks after transplanting and the final application was done before flowering. Daily watering was carried out to maintain approximately the field capacity by measuring soil moisture level using a soil moisture probe which measure the soil volumetric moisture content. Water was added to each pot to reach 100% moisture content.

6.3.2.3 Establishment of weed competition treatment

In 2012, weed competition treatments were established by growing six common lambsquarters (*Chenopodium album* L.) plants with six wheat plants. Due to the high level of competition observed in 2012, three wheat plants and three common lambsquarters plants were used in each pot in 2013. The wheat variety AC Lilian was used in the study as it was the variety used in the ACS field study. Both common lambsquarters (weed) and wheat (crop) seeds were initially germinated in petri dishes in order to transplant them in the pots. Transplanting both weed and crop allowed eliminating any competitive advantage of early emergence. Planting dates depended on the soil sampling carried out in the particular year. In 2012, transplanting was carried out on 15th of June and in 2013 it was done on the 7th June.

6.3.3 Data collection and data analysis

In this study, crop biomass was taken as a proxy for crop yields as the experiment had not enough replicates to do both biomass sampling and grain yield sampling. Also, it was not possible to carry out the experiment until grain-fill stage due to potential nutrient depletion and the low soil volume in the pot. At weed physiological maturity (when weed seeds were produced and matured) all plants (crop and weed) were cut from the base and bagged separately. The samples were air dried for 3 days and weighed. The crop yield loss index was calculated using crop biomass differences in weedy and weedy plot in each cropping system and then expressing it as a ratio from the weed-free crop biomass yield. Crop biomass, weed biomass, total plant biomass and yield loss index data were analyzed using ANOVA using the MIXED procedure in SAS 9.3 (SAS Institute 2011). Data were tested for the assumptions of ANOVA using Levene's test and the normality test. Data for the two years (2012 and 2013) were combined for the analysis and the year was considered as a fixed effect due to the differences in the magnitude of treatments between the two years. All the other treatments such as input, rotation, competition and fertilizer were considered fixed effects and the replication was considered random. Means were declared significant with the LSD test when $P < 0.05$.

6.4 Results

6.4.1 Crop biomass

Crop biomass differed between the two years (two studies) as the two experiments differed in plant densities and the amount of fertilizer being added. In 2012, crop biomass was 47% lower compared to the biomass in 2013 (data not shown). Competition was greater in 2012 since each pot had six wheat and six lambsquarters plants and in 2013, it had only three wheat and three lambsquarters plants. There was a year by competition by fertilizer interaction affecting crop biomass (Table 6.2). In 2012, there was no difference in crop biomass between the two fertilizer treatments for both weedy and non-weedy conditions (Figure 6.1). However, in 2013, fertilized treatments under both weedy and non-weedy conditions had greater biomass compared to non-fertilized treatments (Figure 6.1). Even under weedy conditions, adding fertilizer increased the crop biomass by 43%.

Overall, crop biomass depended on the input by weed competition interaction (Table 6.2). Crop biomass were similar between the two systems under weedy conditions, but ORG systems had 14% lower crop biomass compared to the CONV systems under weed free conditions (Figure 6.2). Crop biomass was also affected by the input by fertilizer interaction (Table 6.2). In both years, in both ORG and CONV systems, adding fertilizer increased the crop biomass (Figure 6.3). In CONV systems, the increase in crop biomass due to added fertilizer was 69% and for ORG it was 50%. Interestingly, even after adding fertilizers, ORG systems had low crop biomass than CONV systems. When standard ORG (non-fertilized) was compared to the standard CONV (fertilized), crop biomass were significantly low (43%) in the standard ORG soils. When both systems were not fertilized, there was no difference in crop biomass between the two systems (Figure 6.3). Similar results were observed in a field experiment by Halde et al. (2015) where they found that when synthetic fertilizer was not applied, conventional systems had similar crop yields to that of organic systems.

Crop rotations had a significant effect on crop biomass (Table 6.2). Crop rotations resulted in differences in crop biomass regardless of all other treatments, indicating the strong influence of crop diversity on crop biomass yield. The HIGH diversity rotation had the greatest crop biomass compared to MEDIM and the LOW rotation (Figure 6.4). Furthermore, no interactions in crop rotations with fertilizer treatments on crop biomass indicated that crop rotations did not respond differently to added fertilizer.

Table 6.2. ANOVA for the effect of year, input, rotation, fertilizer and competition on crop biomass, weed biomass, total biomass and crop biomass loss assessed in the greenhouse in 2012 and 2013.

Treatments	Crop BM ±	Weed BM	Total Plant BM	Crop BM loss
Year (Y)	<.0001	<.0001	0.0254	<.0001
Input (I)	0.0151	0.3978	0.7361	0.5888
Rotation (R)	0.019	0.2262	0.0445	0.4632
Competition (C)	<.0001	NA	NA	NA
Fertilizer (F)	<.0001	<.0001	<.0001	0.0007
Y x I	0.6103	0.899	0.5342	0.8255
Y x R	0.3339	0.9049	0.7528	0.9088
Y x C	0.225	NA	NA	NA
Y x F	**<.0001**	**0.0003**	**<.0001**	**0.0588**
Y x I x R	0.6722	0.9908	0.7478	0.8285
Y x I x C	0.3963	NA	NA	NA
Y x I x F	0.7277	0.634	0.7329	0.4022
Y x R x C	0.9047	NA	NA	NA
Y x R x F	0.9694	0.1128	0.2866	0.2888
Y x C x F	**0.0001**	NA	NA	NA
Y x I x R x C	0.2833	NA	NA	NA
Y x I x R x F	0.33	0.9868	0.5539	0.1448
Y x R x C x F	0.4017	NA	NA	NA
Y x I x C x F	0.2432	NA	NA	NA
Y x I x R x C x F	0.5625	NA	NA	NA
I x R	0.4439	0.7756	0.3238	0.8705
I x C	**0.0213**	NA	NA	NA
I x F	**0.0589**	**0.0138**	**0.0049**	0.2966
R x C	0.1508	NA	NA	NA
R x F	0.7496	0.4321	**0.0376**	0.0761
C x F	**<.0001**	NA	NA	NA
I x C x F	0.3487	NA	NA	NA
I x R x F	0.1086	0.5996	0.6022	0.3378
I x R x C	0.8427	NA	NA	NA
R x C x F	0.5145	NA	NA	NA
I x R x C x F	0.1936	NA	NA	NA

± denotes data were log transformed before analysis.
BM-biomass.
NA-not applicable.

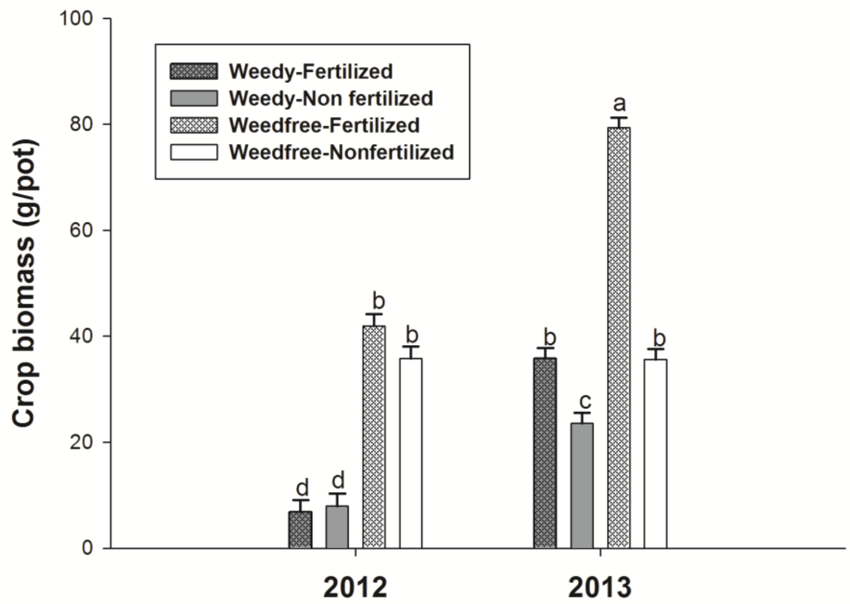

Figure 6.1. The effect of weed competition and fertilizer addition on crop biomass assessed in the greenhouse in 2012 and 2013. Error bars represent back transformed standard errors of the treatment means (pooled across two years with n=3). Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.

6.4.2 Relative biomass loss (crop tolerance to weed competition)

There was no effect of cropping systems or the addition of fertilizer on crop yield loss (Table 6.2) indicating that crop tolerance to weed competition was similar across all cropping systems. Addition of fertilizer significantly increased yield loss from 31% to 52% in 2013 (Appendix D) but not in 2012 (Table 6.2). This difference could be due to higher fertilizer added in 2013 compared to 2012.

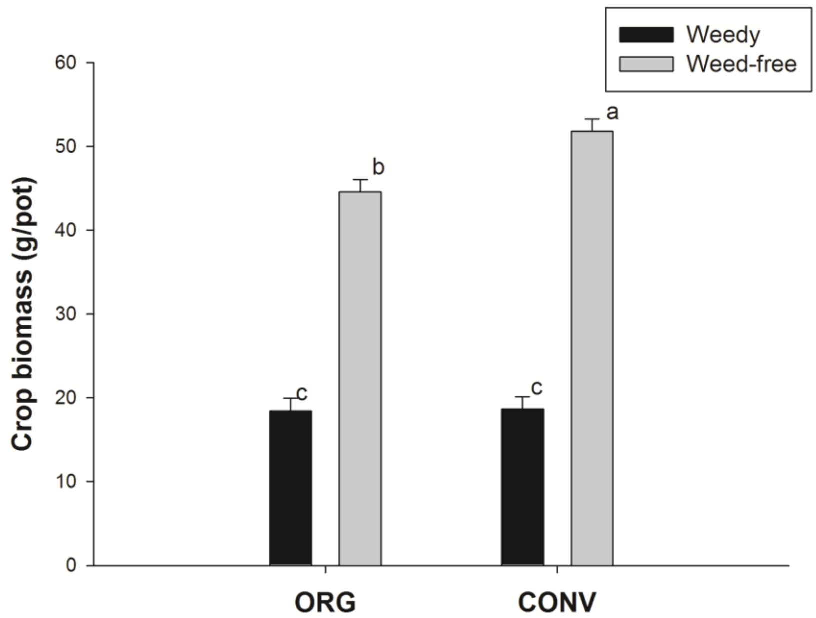

Figure 6.2. The effect of input level and weed competition on crop biomass assessed in 2012 and 2013. Error bars represent back transformed standard errors of the treatment means (pooled across two years with n=3). Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.

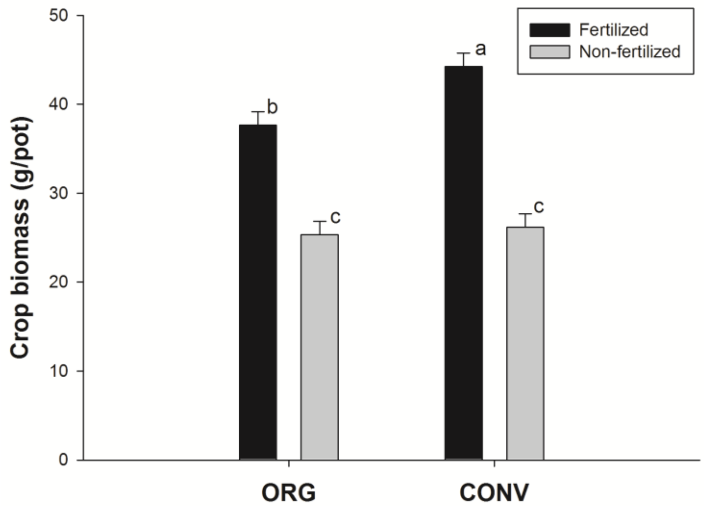

Figure 6.3. The effect of input level and fertilizer addition on crop biomass assessed in the greenhouse in 2012 and 2013. Error bars represent back transformed standard errors of the treatment means (pooled across two years with n=3). Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.

6.4.3 Weed biomass

Weed biomass was greater under both fertilized and non-fertilized conditions in 2012 than in 2013 (Figure 6.5A). This was due to greater weed density in 2012 compared to 2013. Addition of fertilizer increased weed biomass in both input systems in both years (Figure 6.5B). Weed biomass was increased by 82% in CONV systems, but it was only a 42% increase for ORG systems. Standard ORG systems (non-fertilized) had a lower weed biomass compared to the standard CONV (fertilized) systems. When fertilizer was added to ORG systems, weed biomass were similar to that of the standard CONV system. This suggests that the low weed biomass observed in standard organic systems compared to RED systems is due to soil nutrient related low productivity in ORG systems and not due to greater weed suppressive ability.

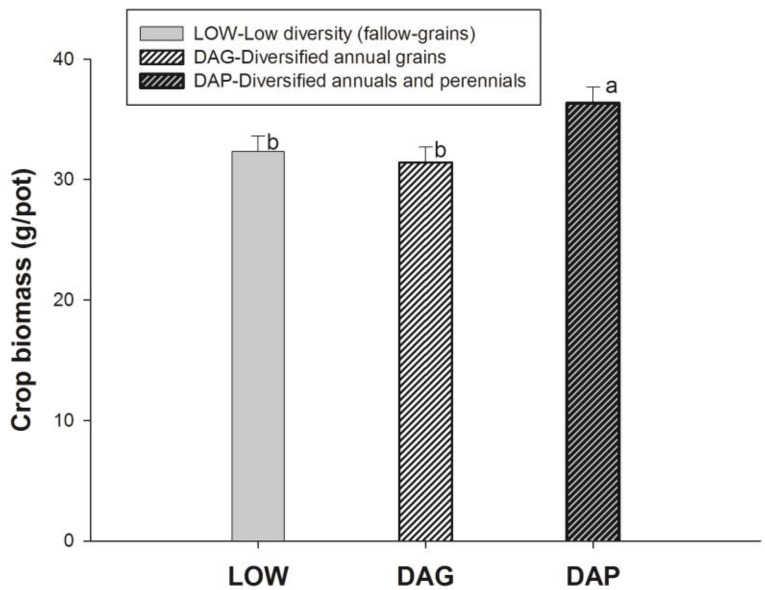

Figure 6.4. The effect of crop rotation on crop biomass assessed in 2012 and 2013. Error bars represent back transformed standard errors of the treatment means (pooled across two years with n=3). Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.

6.4.4 Total productivity (Total plant biomass)

Under non-fertilized conditions, ORG systems had similar total biomass (crop + weed) to that of CONV systems (Figure 6.6A). However, total biomass was greater in CONV under fertilized conditions. Total plant biomass was greater for the standard CONV system (fertilized) compared to the standard ORG system (Non-fertilized). Importantly, there was no difference between the crop to weed biomass proportions under both fertilized and non-fertilized conditions.

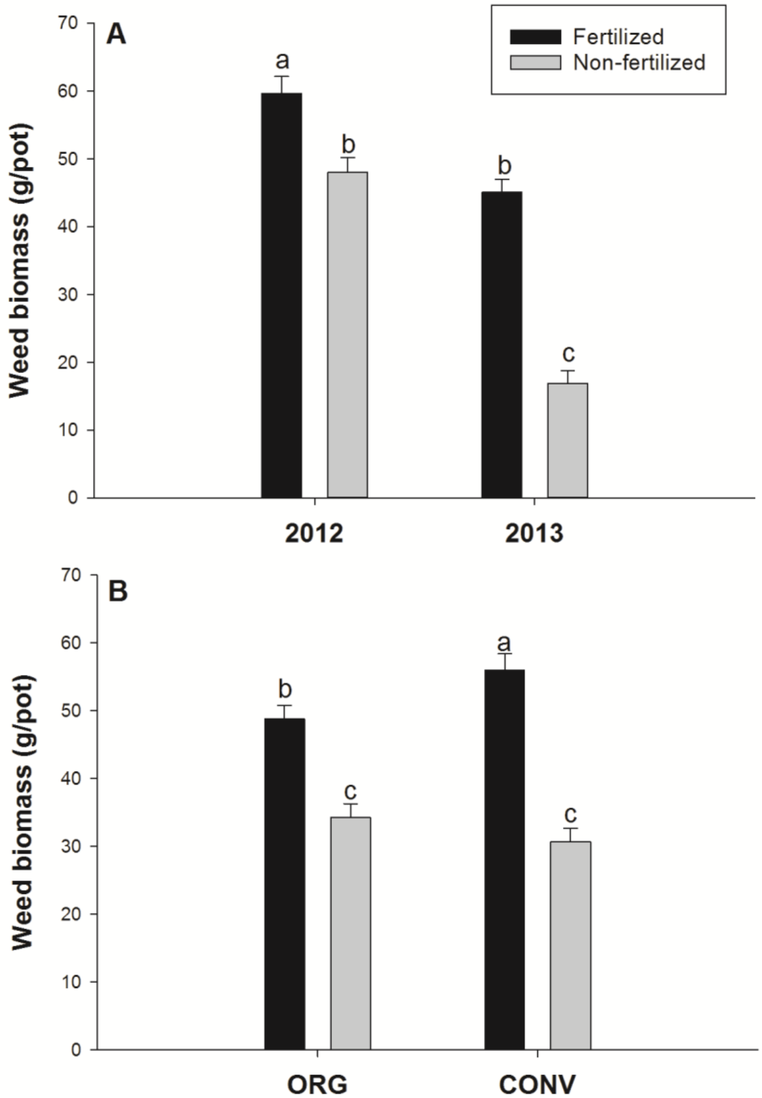

Figure 6.5. The effect of the (A) year and (B) input on weed biomass assessed in 2012 and 2013. Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.

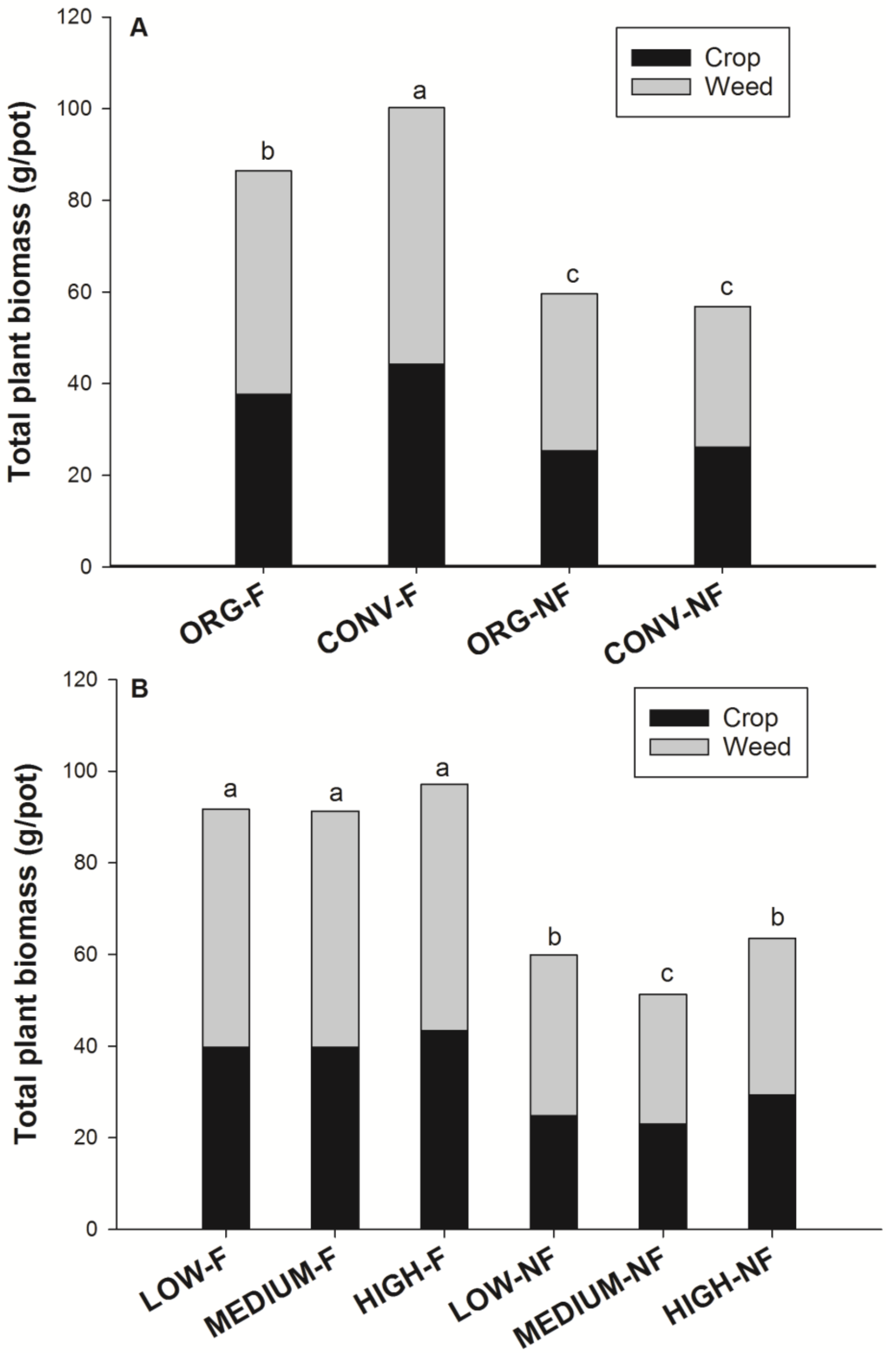

Figure 6.6. Effect of (A) input and fertilizer addition and (B) crop rotation and fertilizer addition on the total plant biomass assessed in 2012 and 2013. Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.

Total plant biomass was similar across crop rotations under fertilized conditions, nevertheless under non-fertilized conditions, the DAG rotation had lower biomass compared to the other two rotations (Figure 6.6B).

6.5 Discussion

Greater crop tolerance to weed competition was not identified in the standard organic systems in this study as the yield losses were similar to the standard conventional systems. Differences in crop tolerance to weed competition in the field were not identified in the ACS study as well (Chapter five). In the field study it was speculated that soil quality related benefits were not found in organic systems due to overall low crop productivity probably due to the low availability of N and P. However, low yield losses were not identified in this study even when mineral fertilizers were added to immediately overcome the low productivity in organically managed soils. Thus, both studies revealed that grain based organic systems in the prairies does not have better crop tolerance to weed competition to that of no-till conventional systems. Hence, these results do not support the resource pool diversity hypothesis proposed by Smith et al. (2010). In a similar greenhouse study, Poffenberger et al. (2015) did not find crop management induced over-yielding effect on crop-weed mixtures due to N resource partitioning. Hence, crop management induced crop tolerance to weed competition is not a universal thing for organic systems.

Yield loss due to weed competition is thought to be one of the most yield limiting factors in organic systems. In this study, we found that crop yields were 14% lower in the organic systems compared to the conventional even under weed free conditions. Thus, this study indicates that even in the absence of weeds, crop yields can be still depressed in the organic systems compared to conventional systems. A field study in the same cropping systems trial (Chapter 5) found that crop yields were about 45% lower in the organic systems compared to conventional systems even under weed free conditions. Organic soils in this study were found to have lower crop biomass production than the conventional soils under standard crop management conditions indicating lower soil productivity. In the field study in the same cropping systems experiment (Chapter five) there was lower biomass productivity in organic systems compared to conventional. Overall, both studies revealed that these organic systems have lower crop yields than conventional, and weed competition was not the main cause for the yield differences. These results suggest that typical grain based organic crop rotations on the Canadian prairies cannot have comparative crop yields of conventional systems because of reduced soil fertility. This current study identified that the organic systems responded to the external addition of N and P by increasing the crop biomass by 50%, confirming that these organic soils deprived of essential nutrients such as available N and P. This study also supported the other studies (Chapter five; Malhi et al. 2009) that N fixing annual green manure crops and perennial forage crops used in the ACS study does not provide sufficient soil nutrients. Furthermore, most grain based organic farms in the prairies has been found to be deficient in plant available P and N (Entz et al. 2001; Martin et al. 2007; Roberts 2008; Knight et al. 2010). Therefore, we can accept the hypothesis that grain based organic systems lack plant available N and P and by increasing the plant available N and P we can increase crop yields substantially.

Soils of organically managed systems are expected to have greater crop yields than the conventional systems when essential nutrients are not limiting due to better soil quality related factors associated with high SOM. However, in this study, it was identified that crops grown on organically managed soils had reduced crop biomass production than conventional system even when the plant available nutrients are not limiting. Since soil organic matter content is one of the most important factors determining soil fertility, low amounts could hinder the potential benefits of organically managed soils. Malhi et al. (2009) found that in the in the ACS cropping systems study after 12 years, the light fraction organic matter (the fraction of SOM that is most active in nutrient cycling) was lower in ORG compared to CONV (RED) system. Therefore, in the ACS cropping systems study, the lack of organic matter in organically managed soils could be the main reason for not observing soil quality related benefits such as greater weed tolerance or greater crop yields than the conventional soils even when essential macronutrients are not limiting. Most organic systems that have found greater soil organic matter content and subsequent soil quality related benefits achieved due to the larger inputs of farmyard manures (Johnston 1997; Clark et al. 1998; Bulluck et al. 2002; Edmeades 2003; Kirchmann et al. 2008; Ryan et al. 2010) but such management is not common in all organic systems, particularly in grain based systems (Knight et al. 2010). In a review using long-term cropping systems studies, Edmeades (2003) found that even though the addition of manure consistently increased organic matter, there was no difference in productivity between manure applied soils and fertilizer applied soils under similar amount of input levels. However, he found exceptions in two long-term Rothamstead trials (Broadbalk and Hoosefield) where crop productivity was greater in manure applied soils compared to fertilizer applied soils suggesting that the application of very high amounts of farmyard manure (35T/ha/year) for hundred years could be the reason for gaining such yields. Also, it was identified that the soil organic matter content was three times greater in manure applied treatments than the fertilized treatments on those two trials. Overall, the Rothhamstead study suggests that in order to gain additional soil quality related benefits from soil organic matter beyond its nutrient supplying ability, large amounts of organic matter need to be applied to the soil over a long-period of time. Therefore, soil quality related benefits may not be found in most grain based systems, particularly due to the absence of continuous addition of organic matter.

Other than low input of organic matter into the system, the intensive use of tillage in the organic systems may have negated the benefits expected from organic soils in the present study. On average, ORG systems in the ACS received four tillage operations per year, while no-till conventional system received no tillage operations in this study (Brandt et al. 2010). Excessive tillage disrupts micorrhizal colonization and thereby affects P availability (Evans and Miller 1990; Abbott and Robson 1991). Furthermore, it can reduce the organic matter content and subsequent benefits of organic soils (Franzluebbers et al. 1999; Weil and Magdoff 2004; Grandy et al. 2006). In cropping systems where external manure was not applied, SOC tend to deplete in organic systems (Riley and Eltun 1994; Breland and Eltun 1999; Fliessbach and Mäder 2000; Kirchmann 2007). The results of this study also support others (Trewavas 2004; Nelson and Spanner 2010) who found that soil quality may be reduced in tillage based organic systems compared to no-till conventional systems. These studies and the present study suggest that overall crop management practices in grain-based organic systems are inadequate to obtain the soil quality related benefits. Therefore, further studies should be carried out to determine the impact of these cropping systems on soil organic matter dynamics to further reveal the problems associated with organic systems.

Improved soil conditions in no-till conventional systems in this study may be another main reason that much of the anticipated soil related benefits in tillage based organic systems compared to conventional was not found. Well managed conventional systems with either no-till or minimum tillage systems with inorganic fertilizers can have similar or better soil biological fertility (Nelson and Spaner 2010), superior soil quality (Trewavas 2004) and other ecosystem services (Robertson 2000) compared to tillage based organic systems. Accordingly, high crop diversity and greater amount of crop residue in these conventional no-till systems and adequate available nitrogen due to synthetic fertilizers may have caused better soil fertility in the conventional systems than tillage-based organic systems in this study. Applying synthetic fertilizers also can contribute to building up soil organic carbon either through enhanced crop biomass production or due to other processes (Paustian et al. 1997). Therefore, it might be necessary to move towards no-till or reduced till organic farming in the future to gain better benefits from organic practices. Yet, no-till organic is still at its infancy in terms of adoption and research as there are some other issues, particularly perennial weed control that remain defiant obstacles.

6.6 Conclusions

Long-term organically managed grain-based cropping systems were found to have lower biomass yields compared to no-till conventional systems. However, yield loss due to weed competition was not the main yield limiting factor in organic systems. There were lower yields than conventional despite no weed competition indicating that these organic cropping systems lacked soil productivity. Adding N and P substantially increased the crop biomass yield of the organic systems indicating that these organic systems are N and P deprived. However, addition of surplus N and P did not increase crop yields of organic systems above the no-till conventional systems indicating that there is no superior soil quality related factors in organic systems as anticipated compared to conventional systems. Furthermore, better crop tolerance to weed competition was not observed in organic systems, even when available nutrients were excess in both systems. In both input systems, having a perennial forage in the rotation increased crop biomass yields, but did not increase crop tolerance to weed competition. Overall, these grain-based organic systems found to have no soil related advantage over no-till conventional systems. Hence, in order to increase crop yields and to reduce yield loss due to weed competition, it is essential to devise better crop rotations and reduce tillage as much as possible to enhance the quality and the quantity of soil organic matter.

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7.0 GENERAL DISCUSSION

The overall objective of this thesis was to understand the weed dynamics (weed abundance, crop-weed competition and weed community composition) and its impacts on crop yields under diverse cropping systems in the Canadian prairies. Furthermore, the suitability and the sustainability of the different cropping systems in reference to weed competition and crop yields were assessed. Cropping systems in the Canadian prairies have been transformed from the tillage-based high-input low diversity cropping systems to no-till conventional with reduced inputs and or organic systems with different crop rotation diversities. Therefore, I hypothesized that the long-term practice of these diverse cropping systems in the prairies differentially affects weed abundance, weed community composition and crop-weed competition; thereby, causes differences in crop yields. Based on the outcome of the thesis I was able to develop some insights to the following key issues in the prairie cropping systems.

7.1 Major findings of the thesis

7.1.1 The outcome of eliminating tillage and reducing synthetic inputs in conventional cropping systems

The results from chapter three revealed that no-till conventional system (RED input) had similar crop yields to that of the tillage-based HIGH input system. Tillage-based conventional crop production is discouraged in the prairies, particularly in the arid regions due to the soil degradation caused by intensive tillage. Based on 18 years of data, this study found that crop yields were comparable between the two systems. Other studies also found that no-till systems have similar crop yields to conventional tillage systems (Kapusta 1996; Nyborg and Malhi 1989; Grandy et al. 2006). However, tillage was considered essential in controlling weeds in most cropping systems and there are many concerns about the long-term negative impacts of no-till crop production on the increase in weed abundance (Blackshaw et al. 1994; Clements 1994; Blackshaw et al. 2001; Derkson 2002). In this study, I found that weed densities were similar between HIGH and RED input systems. Most other studies which found higher weed densities in no-till system are based on the short-term response to no-till. Even though there can be an increase in weed abundance in the short-term, no-till systems have not been found to increase weed abundance compared to tillage systems over the long-term.

Eliminating tillage is widely reported to change the weed composition, particularly colonization of difficult to control weed species. No-till systems are also found to associate with an increase in perennials, grasses, wind-borne species and volunteer crops (Hinkle 1983; Froud-Williams et al. 1983; Allmaras and Dowdy 1985; Froud-Willliams 1988; Thomas and Frick 1993). Increase in perennial weed species was initially thought to be a threat of adopting no-till systems (Cardina et al. 1991; Swanton et al. 1993; Moyer et al. 1994; Zanin et al. 1997). However, based on the longitudinal analysis of the weed community composition over 18 years (chapter four) it was found that such a change in composition does not always occur. In ACS system, no contrasting compositional difference in weed communities between the no-till conventional and tillage based conventional systems (RED versus HIGH) were identified. In particular, we did not find an increase in perennial species in the no-till systems. Similarly, Derksen et al. (1993) also found that the tillage itself may not influence changes in community composition. However, we observed an association of volunteer crops in the no-till system. Importantly, this study found that temporal fluctuations are more prominent than directional changes in the weed community composition. Year-to-year temporal fluctuations in the weed community identified in that study could possibly be due to the rainfall driven random environmental changes. Since there are no differences in weed densities, weed composition and crop yields between the two systems, despite eliminating tillage and reducing the use of herbicides, no-till reduced input system (RED) can be a sustainable alternative to the HIGH input system in the long-term in the prairies.

7.1.2 The effect of eliminating synthetic inputs on weed dynamics and crop yields

The results from chapter three and five revealed that eliminating synthetic inputs such as herbicides and fertilizers in organic agriculture systems increased weed abundance and decreased crop yields. Consistently higher weed density and weed biomass in organic systems were found in most years throughout the eighteen-year period of this study. According to chapter five, the in-crop weed control methods used (mainly harrowing) were unable to provide sufficient weed control in the organic systems. Therefore, this study revealed the necessity of developing more effective weed control methods for organic systems. Crop yields in organic were found to be consistently low throughout the period in comparison to the two conventional systems. Despite increasing trends in weed abundance, organic systems showed increasing crop yields over time, possibly indicating less impact of residual weed abundance on crop yields. In this study, we did not find a direct relationship between weed abundance and crop yield probably due to less competitiveness of residual weeds on the well-established crop. However, effective weed control methods are required to keep the weed densities low to acceptable levels in order to maintain harvest crop quality and to avoid buildup of the soil weed seed bank over time. Organic systems had consistently different community composition throughout most years compared to the two conventional systems, mostly due to the high weed abundance caused by the inability to control weeds. In particularly, the species diversity was found to be higher in organic compared to the two conventional systems. Yet, the impacts of these changes in species composition on crop yields are not known.

7.1.3 The impact of increasing crop rotation diversity on weed management and crop yields

Surprisingly, chapter three revealed that increasing the crop diversity from fallow-grains to continuous diverse annual cropping or annual-perennial cropping resulted in an increase in weed density and weed biomass in both conventional and organic systems. Both weed densities and weed biomass were lowest in the low diversity rotation (crop-crop-fallow) compared to the other two rotations (Chapter three). A fallow period in crop rotations has often been found to have beneficial effects on weed control (Hume 1982; Blackshaw 1994; Derksen et al. 1994). Hence, even though the crop diversity was low in the LOW diversity rotation, having a fallow period benefited weed control compared to continuous crop rotations. Use of extensive tillage in the fallow period in HIGH-LOW rotation and use of herbicides in conservation fallow in RED-LOW rotation probably have helped to reduce weed densities during the rotation cycle. In contrast, increasing the crop diversity in rotations has been generally found to reduce weed abundance (Liebman and Dyke 1993) and is believed to be the key strategy for the long-term weed management particularly in organic systems. A rotation with crops of different life cycles and phenology than the monoculture is generally known to be more disruptive for the weed life cycle. Accordingly, Entz et al. (1995) identified that in majority of farms in Canada, having a three-year alfalfa crop in the rotation reduced weed abundance. Furthermore, Kegode et al. (1999) identified that there was a low weed seed production when includes a perennial crop in the rotation. However, most previous studies which revealed the advantages of crop rotation was mainly in comparison to continuous monocropping; hence, the results of this study should not be misinterpreted to reveal that crop diversity is not beneficial compared to monocropping as this study did not compare crop rotations to monocropping. Since crop-fallow system is a very effective system in controlling weeds, the benefits of a more diverse crop rotation in terms of weed control may have not been apparent in this study.

Increasing the crop diversity from crop-crop-fallow to more diverse crop rotations did not result in increased crop yields (Chapter three). Crop yields were found to be higher in the low diversity rotation compared to a more diverse DAP rotation which used both annuals and perennials. Having a three-year perennial alfalfa crop in the rotation was found to decrease crop yields in all the three input systems in this study. Perennial crops have been found to deplete nutrients and moisture in some regions, thereby deterring crop yields (Bell et al. 2012). The results from chapter five also revealed that overall plant biomass production is significantly lower in the DAP systems, particularly in the organic input systems. This reveals that soil productivity is low in these perennial based rotations. Inclusion of a three-year alfalfa crop in the rotation in this study did not result in any benefits in terms of crop yields or weed management either in organic or conventional systems. Theoretically, the long duration of canopy cover provide by alfalfa should suppress weed emergence; however, it was observed that there was often poor establishment of the alfalfa which negatively affect weed management. Furthermore, most benefits of perennial crops such as high yields and weed control could only be exploited under humid conditions with adequate rainfall whereas negative effects can be observed under semi-arid environments (Pikul et al. 2005). Hence, annual legumes could be a better option for drier areas (Biederbeck and Bouman 1994). Therefore, the choice of the crop rotation should be determined by the soil and climatic conditions in the region. Since these rotations were not found to be effective in controlling weeds and increasing crop yields, inclusion of perennials in the rotation should be considered with care.

7.1.4 The impact of cropping systems on crop-weed competition

Although there is an overwhelming body of research which has studied the impact of cropping practices on weed abundance, there is a very limited amount of research studied the impact of weeds on crop yields and how the yield losses due to weed competition differ among cropping systems. High weed densities are often believed to be the main factor that reduces crop yields. Particularly, it has been considered as the main debacle in organic and low-input systems. But this thesis (chapter three and five) revealed that weed densities may not always be directly related to yield differences in cropping systems. Furthermore, there was no direct relationship identified among weed abundance (weed density, weed biomass) and crop yields. Hence weed density should not be considered as the sole predictor of crop-weed competition or yield loss. The impact of weeds on crops depends on many factors such as the timing of weed emergence, competitive ability of weeds, competitive ability of crops and importantly the crop management practices.

This lack of a relationship between weed abundance and crop yields in this study and in some other studies ((Delate and Cambardella 2004; Davis et al. 2005; Hiltbrunner et al. 2008; Ryan et al. 2010) suggest that cropping systems differ in crop-weed competition. Hence, there is some evidence that yield loss due to weeds can be managed by reducing crop-weed competition through better soil management practices (Ryan et al. 2009; Smith et al. 2010). Accordingly, the study in chapter five was carried out to compare yield loss due to weeds under organic and conventional systems (Chapter five). The results revealed that the yield losses were similar between organic and reduced input systems and also crop diversity did not affect the yield loss. However, the inability to find differences in yield loss between organic and conventional systems in our study does not necessarily refute resource diversity hypothesis (Smith et al. 2010). According to Smith et al. (2010), the diversity in soil resource pools among cropping systems is the fundamental mechanism that can cause differences in crop-weed competition. Thus, to observe these difference cropping systems need to be diverse in soil resource pools. The inability to find differences in yield loss (crop tolerance) among these cropping systems could be due to many reasons. These organic systems mainly relied upon green manure as the soil fertility source since the use of farmyard manure was minimal. Furthermore, the excessive use of tillage in organic systems can deplete organic matter content (Franzluebbers et al. 1999; Weil and Magdoff 2004; Grandy et al. 2006). Furthermore, no-till conventional systems are fertilized; thus being more productive, thereby return more organic matter to the soil than organic systems. Therefore, these grain-based organic systems may not have the diversity in soil resources compared to the no-till conventional systems. Furthermore, substantially low crop yields in organic systems (Chapter three and five) could be another reason that we could not find better crop tolerance to weed competition.

7.1.5 Factors hindering crop yields in organic compared to conventional cropping systems

Crop yields in organic systems are usually substantially lower than those in conventional systems. In this study, we found that average crop yields in organic were 32% and 35 % lower than RED and HIGH systems. These differences are in accordance with most other studies which found similar low crop yields (Seufert et al. 2012; Ponisio et al. 2015). However, these differences in yields are based on overall crop yields average across all crop phases, hence, the type of crops and the number of crop phases in each input system can influence the mean yield. But this overall comparison of crop yields is more appropriate than the comparison of individual crop phases among systems (Kirchmann et al. 2016) as it does not reflect the overall crop production system. High weed densities and low soil fertility are the two major reasons for these differences in crop yields. However, since both factors confound each other, the relative significance of each factor is not known. Wheat yields were found to be significantly lower in the organic system even when there were no weeds present, implying soil related factors are causing lower yields in organic. Importantly, the overall plant biomass production (crop +weed) was also found to be lower in organic rotations compared to conventional systems. Hence, we can confirm that soil productivity was lower in the organic systems than the conventional systems. Low soil productivity in these grain based organic systems could be mainly due to lack of mineralizable soil N and P. Organic cropping systems in the Canadian prairies mainly rely on nitrogen fixing legumes to replenish soil nutrients exported with the crop at harvest. Even though farmyard manure is considered as a rich source of nutrients (Schoenau et al. 2010), the availability of farmyard manure is limited in the prairies due to majority of organic farms do not have livestock (Shirtliffe et al. 2005: Knight et al. 2010). Thus, most organic farms in the region are P and N limited (Entz et al. 2001; Martin et al. 2007; Roberts 2008). Similarly, Malhi et al. (2009) has revealed low soil N and soil P in the organic compared to conventional rotation in a previous study on this crop rotation experiment. Therefore, we have enough evidence to conclude that these cropping systems are depleted with essential nutrients.

7.1.6 Can organic systems benefit by increasing available essential nutrients

Since low soil fertility was found to be the main reasons for not observing better crop tolerance to weed competition in organic, adding essential nutrients should increase crop yields in organic systems and as well increase crop tolerance to weed competition. Chapter six in this thesis tested this hypothesis using a greenhouse study. The results of chapter six revealed that soil available N and P were the most limiting factor in organic systems, since an excessive supply of soil mineral N and P increased crop biomass by 50 %. However, despite supplying as thought to be excessive amounts of soil N and P, the organic systems did not have a greater crop biomass yield than the no-till conventional system. There was also no indication of greater crop tolerance to weed competition even after soil N and P was added to organic systems. Even though some studies in organic farming found better soil quality (Mäder et al. 2002; Mulder et al. 2003; Birkhofer et al. 2008) and their benefits in weed management (Ryan et al. 2010; Smith et al. 2010), according to the results from both chapters five and six we could conclude that these organic systems do not have any advantage in terms of crop yields or crop tolerance to weed competition compared to no-till conventional systems.

7.2 The importance of environmental factors on weed dynamics

There are several studies carried out to understand the impact of cropping systems on weed abundance and crop yields in long-term experiments (Sosnoskie et al. 2006; Cavigelli et al. 2008; Fried et al. 2008; Ryan et al. 2010). However, the influence of environmental factors has been given less attention. This thesis (Chapter three and four) found that random environmental changes as well as long-term environmental fluctuations can be the biggest driver besides crop management practices on weed dynamics and crop yields. The statistical approaches used in this thesis to analyze long-term data are fairly unique (random spline coefficient models and principal response curve technique) and was powerful to realize the influence of these environmental factors on weed dynamics (Chapter three and four). Chapter three found that weed density and weed biomass are increasing throughout the time beside crop management practices. Increasing in rainfall amounts during the time period found to correlate with crop yields and weed abundance. Furthermore, yearly fluctuations in weed abundance where substantial, therefore year-to-year growing conditions can be more influential than crop management. Similarly, chapter four revealed that the weed species composition is mainly determined by the interactions of environment and crop management factors. Hence, year-to-year fluctuations in species composition is more prominent. Therefore, conclusions based on most agronomy experiments had to be dealt with caution as we cannot preclude the impact of the environment on the outcome of the results. In weed management perspective, unravelling the short term influences of weather conditions demands the need to build up strong, robust integrated weed management approaches to manage weeds within the crop growing season on top of long-term weed management strategies.

7.3 The way forward

7.3.1 Managing the transition to organic from conventional systems

The management of the transition period from conventional to organic can be very crucial for a sustainable organic farming system. Most organic systems require a minimum of three years of a transition period. This transition period is defined in organic certification perspectives to allow some time period to avoid the residual effects of conventional farming contaminating the organic produce. In agro-ecological perspective, it is an abrupt transition from high-external input system to a no-external input system. According to my perspective, this abrupt transition could be the downfall for most of the organic systems that causing low yields and high weed abundance. The results (Chapter six) clearly showed that even in conventional systems, when fertilizers were not applied for one season, the productivity drastically declines even it has been farming for 18 years with synthetic fertilizers. This suggests that the conventionally managed soils have not built up the soil fertility; instead it relies on a continuous application of external fertilizers. Similarly, we found that weed abundance drastically increased in conventional system when herbicides were not applied for one season (Chapter five). Therefore, the immediate exclusion of these conventional crop management practices can immediately cause soil fertility and weed problems.

Here, I suggest that this transition period should be defined agronomically, allowing a smooth transition from intensive input system to an ecological-based system. Instead of completely eliminating external inputs, gradual reduction of inputs is viable throughout a certain period of time while integrating other ecological based crop production practices. Due to the degraded soils and the intensity of crop harvest, the total elimination of synthetic inputs at the end of one production phase can dramatically reduce crop yields either in grain phases or in the green manure phases; thus, producing a chain reaction of events in subsequent crop phases. Particularly, organic systems rely the on the previous crop performances for the subsequent crop than in conventional systems. Here, I suggest that there should be crop rotation phases with integrated approaches for soil fertility management and weed management. Thereby, it can progressively eliminate external inputs while building up on the internal self-regulating cropping system. This smooth transition can be very crucial for grain-based organic systems, particularly with inherent low soil productivity where farmyard manure or compost is not available to instantly replenish soil fertility status. This can be a radical change to organic farming and to the certification process, but there is a growing evidence to suggest that there is a need to take these necessary changes to sustain organic systems throughout the world.

7.3.2 Managing crop rotations

Establishment of a healthy, vigorous crop is the first principle of ecologically based weed management. The main drawback identified in organic rotations in this study is a reduction in crop yields due to lower soil fertility. Low crop yields result from low crop biomass and an uncompetitive crop with weeds. Particularly, when the green manure crop is not well established, a chain reaction of lower crop biomass–lower soil organic matter and lower soil fertility can continue for all crop phases. Establishment of a healthy green manure crop or a forage crop is crucial not only for soil productivity but also for weed management. Suppressing weeds by a good ground cover produce by green manure or the perennial forage crop is the key aspect of weed management. In that perspective, the first crop rotation cycle during the transition to organic can be crucial. The initial crop rotation cycle should be designed to avoid exhausting the nutrients by having grain crops grown one after another. Once soil nutrients are depleted, producing a good green manure crop or a perennial forage crop can be challenging. In organic systems, the inclusion of soil building phases such as green manure crops should increase in frequency in the rotation (2-3 green manure phases) at least during the first rotation cycle. It is important to have a green manure phase after at least every two grain phases within the crop rotation. When the soil fertility is enhanced, it can produce more crop biomass (grain or green manure) and subsequently more crop residues and more organic matter to maintain the soil fertility. This was also identified in the ACS study as the LOW diversity rotation was the most productive and most effective in weed control. Accordingly, the two green manure phases in ORG-DAG system may not be sufficient to maintain the soil fertility. In that rotation, the three consecutive grain crops may have depleted the soil nutrients. Instead, a green manure crop phase after every two grain crop phases might increase the soil fertility in these systems and suppress weeds as well.

From a weed management perspective, it may be more beneficial to select crops that are more competitive and crops that are tolerant for in-crop mechanical weed control. When considering the overall rotation cycle, crop phases with less competitive ability and crops that cannot be harrowed are the ones that can result in an increase in weed abundance and thereby contribute to the weed seedbank. Even though some less competitive crops such as flax and lentil are more economically attractive to organic farmers, avoiding these crops at least during the first rotation cycle should be considered. Even though we did not find an advantage in having a perennial forage crop it should not be totally eliminated in cropping systems. In more suitable environments, perennials should be included every one or two rotation cycles intermittently. Continuing using the same cycle of crop rotations for many years may not be advisable in most circumstances. The results of this study found that three six-year cycles of annual-perennial systems cause a decline in crop yields. Furthermore, perennial crops should be used to manage annual weeds when such problems arise or otherwise kept the frequency to the minimal level in the rotation particularly not in the first rotation cycle. Overall, the crop rotations should be dynamic and it has to be evaluated ongoing basis and adjustments are needed based on crop productivity, weed abundance and weed community changes that can be observed.

7.3.3 Healthy soils key to the success

Overall, the results of this thesis concluded that managing the soil fertility is an upmost priority for grain-based organic farmers in these regions to sustain better crop yields. Even though weed abundance is greater in organic systems, its impact on crop yields are inferior to the impact of low soil fertility. Furthermore, management of soil is a fundamental requirement in managing weeds as well. Even though our study did not support the resource pool diversity hypothesis proposed by Smith et al. (2010), optimally managed, highly productive organic soils can increase crop tolerance to weed competition (Ryan et al. 2010). Hence, increased organic matter content or increase in diversity of resources added to soil might provide benefits in terms of weed management on top of enhancing the soil fertility. Since increasing the external inputs such as farmyard manure is less practical for large scale grain-based farmers, the only potential lies by better management of organic matter added through green manures and by increasing crop residues by reducing or eliminating tillage in these organic systems.

7.4 Final remarks

This thesis was able to provide in-depth insights into weed dynamics under varying cropping systems representing those practiced by prairie farmers. It was able to clearly conclude the suitability of the reduced-input system over the high-input system in terms of weed management and crop yield perspectives based on robust data and advanced statistical analysis. However, this study did not find any advantage of increasing the crop diversity in rotations with perennials over the crop-fallow rotation or the continuous grain rotation in terms of weed management or crop yields. This study revealed the limitations in organic systems compared to the conventional systems and importantly was able to recognize that soil fertility management is the most crucial factor in order to increase crop yields regardless of weed competition. Using two studies, this thesis was able to confirm that there are no differences in crop tolerance to weed competition among organic and no-till conventional system or among diverse crop rotations. Hence, reducing yield-loss due to crop-weed competition is not practical under these cropping systems. Furthermore, drastic changes in weed community composition due to crop management were not identified, but year-to-year changes in weather conditions were the most influential effect on weed community composition. Also, this thesis revealed that no-till conventional systems have better soil productivity than tillage-based organic systems under comparable conditions excluding other confounding factors. Hence, I suggest that moving from tillage-based to no-till systems can be beneficial even in organic systems as well. Furthermore; this thesis critically discussed some of the shortcomings of statistical methods used in analyzing long-term agronomic studies and introduced appropriate new tools to the agronomy and weed science discipline that can assist for better interpretation of data from long-term studies. Hence, this thesis can be a valuable asset, not only towards unravelling new wisdom on weed dynamics, but assist with better research methodologies for the future long-term cropping system studies.

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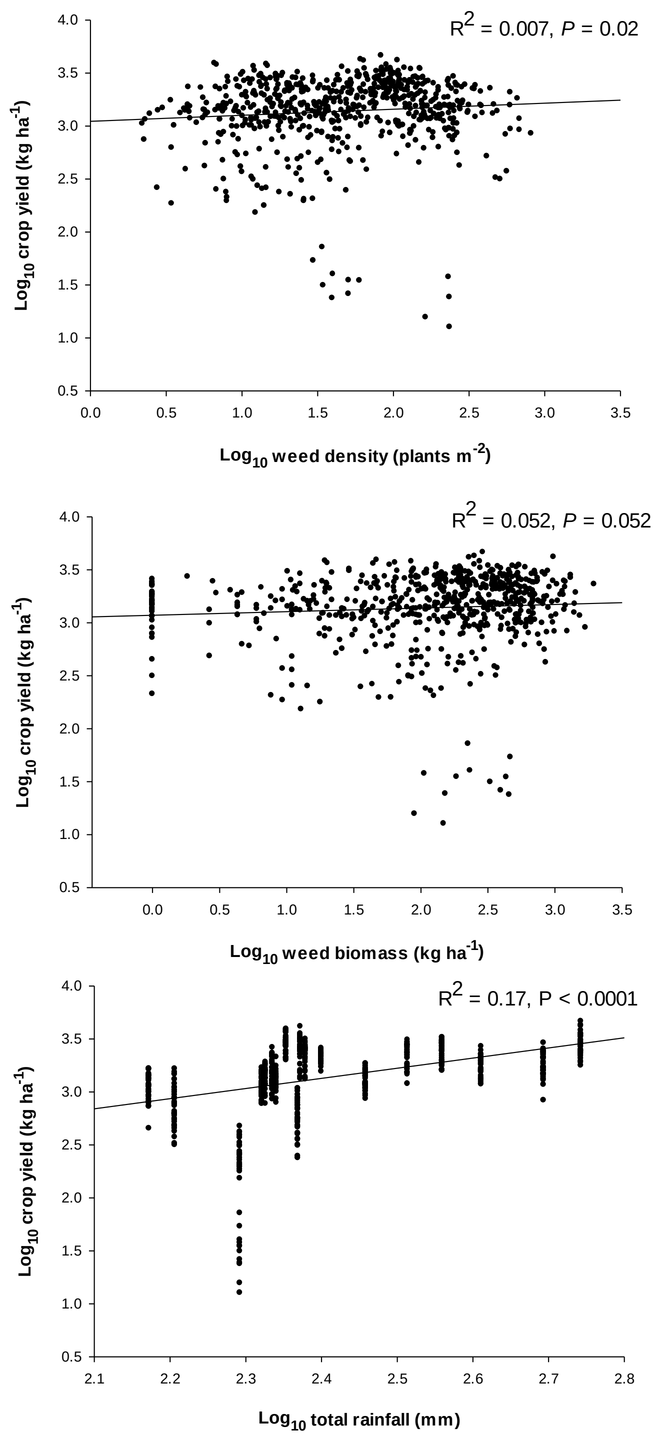
APPENDIX A. Example SAS code used to analyze the data in chapter 1.

```
ods html;
ods graphics on;
proc sort data=ACS; by Time Trt; run;
proc glimmix data=ACS /*nobound*/plots=residualpanel;
nloptions tech=newrap maxiter=1000000;
tim=Time/10;
class Rep Input Rotation;
model yld= Time Input Rotation Rotation*Input/ ddfm=kr dist=g;
random rep*Input;
random tim/grp=Rotation type=rsmooth subject=Rep knotmethod=kdtree (bucket=12 knotinfo);
covtest/Wald;
covtest 'ORG vs Non-Organic'contrast 0 -0.5 -0.5 -0.5 1 1 1 -0.5 -0.5 -0.5;
covtest 'ORG vs RED'contrast  0 0 0 0 -1 -1 -1 1 1 1;
covtest 'ORG vs High'contrast 0 -1 -1 -1 1 1 1 0 0 0;
covtest 'RED vs High'contrast 0 -1 -1 -1 0 0 0 1 1 1;
covtest 'DAG vs DAP' contrast 0 1 -1 0 1 -1 0 -1 1 0;
covtest 'DAG vs LOW'contrast 0 1 0 -1 1 0 -1 0 1 -1;
covtest 'DAP vs LOW'contrast 0 0 1 -1 0 1 -1 1 0 -1;
lsmeans Input Rotation Input*Rotation/slice=Input pdiff adjust=tuckey;
output out=gmxoutyld prep(blips)=predicted lcl(blup)=lcl ucl(blup)=ucl;
output out=gmxoutlyld pred(blup)=predicted lcl(blup ILINK)=lcl ucl(blup ILINK)=ucl;
nloptions tech=newrap;
run;
```

APPENDIX B. The relationship between crop yield with weed density, weed biomass, and total rainfall at ACS, Scott.



APPENDIX C. The ANOVA for the effect of Input and Rotation on Species richness, Species evenness and Shannon Weiner diversity index measured at a wheat phase from 1995-2012 of the ACS at Scott.

Treatment	Species richness	Evenness	Shannon Weiner diversity
Input	0.6485	0.0007	0.0038
Rotation	0.0006	<.0001	0.3203
Input*Rotation	0.0033	<.0001	0.8027

APPENDIX D. The effect of fertilizer addition on crop biomass loss assessed in the greenhouse in 2012 and 2013. Error bars represent back transformed standard errors of the treatment means (pooled across two years with n=3). Comparisons made between treatments with similar letters indicate no significant difference at LSD 0.05.